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(56) Documents cited
GB 1267924
GB 1238797
GB 1060743
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GB 781682
GB 479309
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(58) Field of search
H2A
H2J

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(54) Pole changing induction electrical machines

(57) An induction machine has a core with a number of slots (s) and a double layer winding comprising two phase-windings (A, B) for two-phase operation (Fig. 14a) at a first pole number (2p) using a capacitor C/p. the top layer has conductors assigned to s/4p successive slots for each pole of each of the two phase-windings. Switching means is provided for reconnecting coils or groups of coils of the two phase-windings by pole amplitude modulation to produce a single phase-winding (Fig. 14b) using a centrifugal switch C/S at a second, and possibly also a third, pole number. The positions of the modulating waves producing the second and third pole numbers may be different, e.g. mutually displaced by greater or less than 90° on the scale kΘ, where k is the number of modulating pole pairs in one revolution and Θ is mechanical degrees around the axis. The top layer may have conductors assigned to $s/2p_2$ successive slots for each pole of the second pole number ($2p_2$), except that one or more coils providing conductors in the top layer adjacent one end of each of alternate $s/2p_2$ groups are reversed. Separate modulating waves mutually displaced by less than 180° may produce a second pole number.

FIG. 14(a)

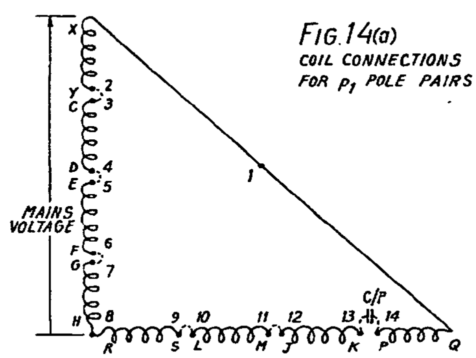
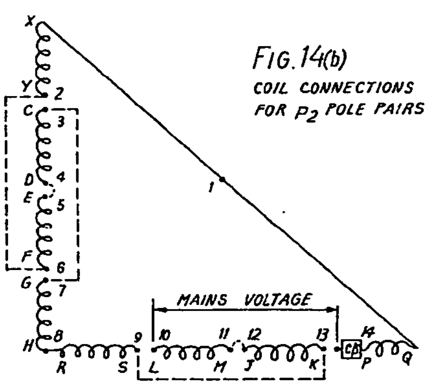
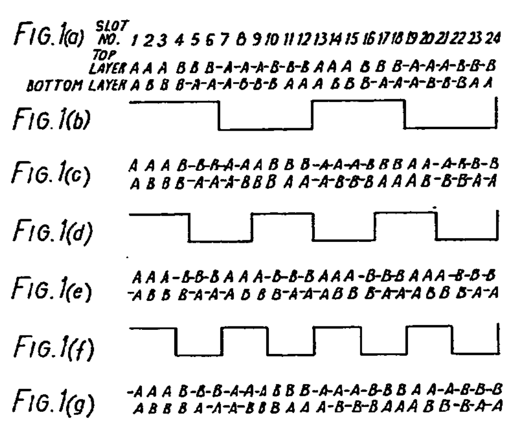


FIG. 14(b)





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Renyan William Fei, et al
SN Not Assigned Yet

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FIG. 1(a)

SLOT NO. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

TOP LAYER A A A B B B -A -A -A -B -B -B A A A B B B -A -A -A -B -B -B

BOTTOM LAYER A B B B -A -A -A -B -B -B A A A B B B -A -A -A -B -B -B A A

FIG. 1(b)

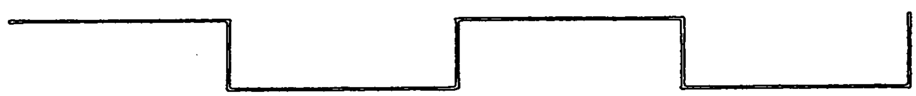


FIG. 1(c)

A A A B -B -B -A -A A B B B -A -A -A -B B B A A -A -B -B -B

A B B B -A -A -A -B B B A A -A -B -B -B A A A B -B -B -A -A

FIG. 1(d)

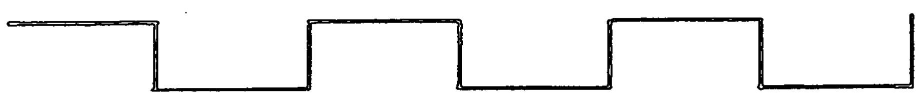


FIG. 1(e)

A A A -B -B -B A A A -B -B -B A A A -B -B -B A A A -B -B -B

-A B B B -A -A -A B B B -A -A -A B B B -A -A -A B B B -A -A

FIG. 1(f)

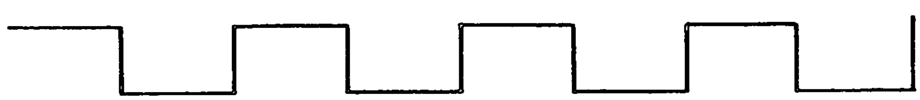


FIG. 1(g)

-A A A B -B -B -A -A -A B B B -A -A -A -B -B B A A -A -B -B -B

A B B B A -A -A -B B B A A A -B -B -B A A A B B -B -A -A

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36

FIG. 2(a)
A A A B B B-A-A-A-B-B-B A A A B B B-A-A-A-B-B-B A A A B B B-A-A-A-B-B-B
A A A B B B-A-A-A-B-B-B A A A B B B-A-A-A-B-B-B A A A B B B-A-A-A-B-B-B

FIG. 2(b)
A A A B B B A A A-B-B-B-A-A-A-B-B-B A A A B B B A A A-B-B-B-A-A-A-B-B-B
A A A B B B-A-A-A-B-B-B-A-A-A B B B A A A B B B-A-A-A-B-B-B-A-A-A B B B

FIG. 2(c)
A A A B-B-B-A-A-A B B B A-A-A-B-B-B A A A B-B-B-A-A-A B B B A-A-A-B-B-B
-A A A B B B-A-A-A-B B B A A A-B-B-B-A A A B B B-A-A-A-B B B A A A-B-B-B

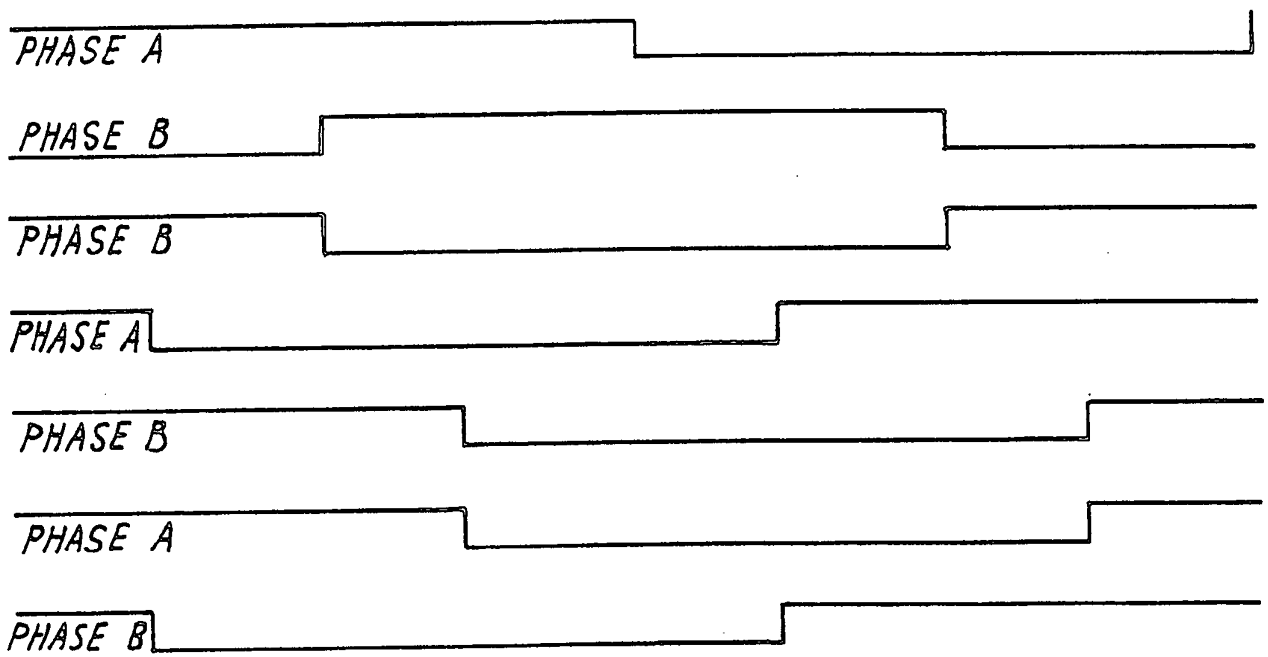


FIG. 2(d)
FIG. 2(e)
FIG. 2(f)
FIG. 2(g)
FIG. 2(h)
FIG. 2(i)
FIG. 2(j)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
A A A A B B B B-A-A-A-A-B-B-B-B A A A A B B B B-A-A-A-A-B-B-B-B
A B B B B-A-A-A-A-B-B-B-B A A A A B B B B-A-A-A-A-B-B-B-B A A A

FIG. 3(a) CONDUCTOR DISTRIBUTION FOR 4 POLES, UNMODULATED

A A A A B-B-B-B-A-A A A B B B B-A-A-A-A-B-B B B A A A-A-B-B-B-B
A B B B B-A-A-A-A-B B B B A A-A-A-B-B-B-B A A A A B B-B-B-A-A-A

FIG. 3(b) CONDUCTOR DISTRIBUTION FOR 6 POLES, MODULATED

FIG. 3(c) MODULATING WAVE FOR PHASE A

FIG. 3(d) MODULATING WAVE FOR PHASE B

FIG.4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
4 POLES	+	+	+				-	-	-				+	+	+				-	-	-				PHASE A
6 POLES	-	+	+				-	-	-				-	-	-				+	+	-				
8 POLES	+	+	+				+	+	+				+	+	+				+	+	+				
4 POLES				+	+	+				-	-	-				+	+	+				-	-	-	PHASE B
6 POLES				+	-	-				+	+	+				-	-	+				-	-	-	
8 POLES				-	-	-				-	-	-				-	-	-				-	-	-	

FIG.5

E $\boxed{1\ 13\ 14\ 15}$ F X $\boxed{2\ 3}$ Y G $\boxed{7\ 8\ 9\ 21}$ H C $\boxed{19\ 20}$ D

L $\boxed{4\ 18}$ M P $\boxed{5\ 6\ 16\ 17}$ Q R $\boxed{10\ 11\ 12}$ S J $\boxed{22\ 23\ 24}$ K

FIG.6

4 POLES
PHASE A XY—CD—EF—GH——TO R
PHASE B RS—LM—JK—PQ——TO X

6 POLES PQ—XY—FE—DC—GH—RS—KJ—ML

8 POLES PQ—XY—DC—EF—SR—HG—KJ—LM

FIG.7

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
PHASE A																																				
6 POLES	+	+	+				−	−	−				+	+	+				−	−	−				+	+	+				−	−	−			
4 POLES	+	+	+				+	+	+				−	−	−				+	+	+				+	+	+				−	−	−			
8 POLES	+	+	+				−	−	−				+	−	−				+	+	+				−	−	−				+	−	−			
PHASE B																																				
6 POLES				+	+	+				−	−	−				+	+	+				−	−	−				+	+	+				−	−	−
4 POLES				+	+	+				−	−	−				−	−	−				+	+	+				−	−	−				−	−	−
8 POLES				+	−	−				+	+	+				−	−	−				+	−	−				+	+	+				−	−	−

FIG.8

X $\boxed{1\ 2\ 3\ 32\ 33}$ Y C $\boxed{7\ 8\ 9\ 13}$ D E $\boxed{14\ 15\ 19\ 20\ 21}$ F G $\boxed{25\ 26\ 27\ 31}$ H

J $\boxed{5\ 6\ 10\ 11\ 12}$ K L $\boxed{16\ 17\ 18\ 22}$ M Q $\boxed{23\ 24\ 28\ 29\ 30}$ P R $\boxed{34\ 35\ 36\ 4}$ S

FIG.9

6 POLES
PHASE A −XY−GH−DC−EF−
PHASE B −JK−SR−LM−PQ−

4 POLES
XY−GH ML−QP
CD−FE JK−SR

8 POLES −XY−DC−FE−HG−KJ−ML−NP−SR−

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
4 POLES	A	A	A	A	B	B	B	B	B	-A	-A	-A	-A	-A	-B	-B	-B	-B	A	A	A	A	B	B	B	B	B	-A	-A	-A	-A	-A	-B	-B	-B	-B
6 POLES	A	A	A	A	B	B	-B	-B	-B	-A	-A	-A	A	A	B	B	B	B	-A	-A	-A	-A	-B	-B	B	B	B	A	A	A	-A	-A	-B	-B	-B	-B
8 POLES	A	A	A	A	B	-B	-B	-B	-B	A	A	A	A	A	-B	-B	-B	-B	A	A	A	A	B	-B	-B	-B	-B	A	A	A	A	A	-B	-B	-B	-B

FIG.10 CONDUCTOR DISTRIBUTION OF THE TOP LAYER AT 4, 6 AND 8 POLES

PHASE A 4 POLES ++++ ----- ++++ -----
6 POLES ++++ ---++ ---- +++--
8 POLES ++++ +++++ ++++ +++++

PHASE B 4 POLES +++++ ---- +++++ ----
6 POLES ++--- ++++ --+++ ----
8 POLES +---- ---- +---- ----

FIG.11 DIRECTION OF CURRENT FLOW FOR PHASES A AND B AT 4, 6 AND 8 POLES

X—$\boxed{1\ 2\ 3\ 4}$—Y G—$\boxed{10\ 11\ 12\ 31\ 32}$—H C—$\boxed{13\ 14\ 28\ 29\ 30}$—D E—$\boxed{19\ 20\ 21\ 22}$—F

J—$\boxed{33\ 34\ 35\ 36\ 5}$—K L—$\boxed{6\ 25\ 26\ 27}$—M P—$\boxed{7\ 8\ 9\ 24}$—Q R—$\boxed{15\ 16\ 17\ 18\ 23}$—S

FIG.12 GROUPING OF COILS ACCORDING TO DIRECTION OF CURRENT FLOW

PARALLEL
CIRCUIT

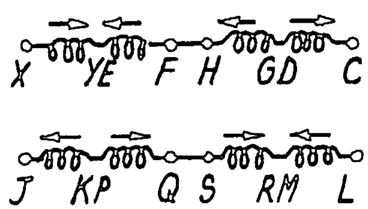


FIG.13(a)

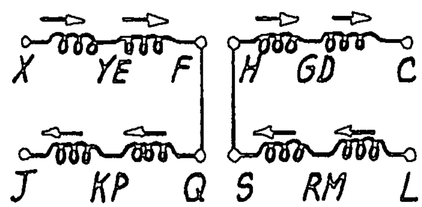


FIG.13(b)

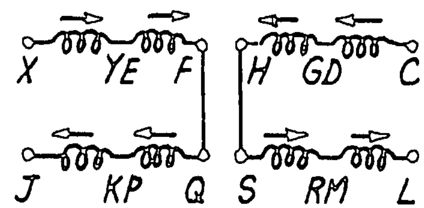


FIG.13(c)

POSITION 1

POSITION 2

POSITION 3

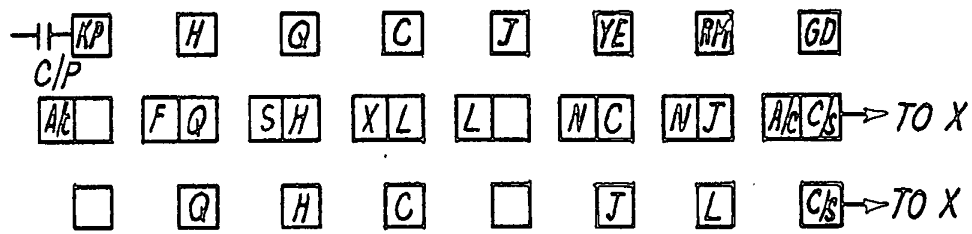


FIG.13(d)

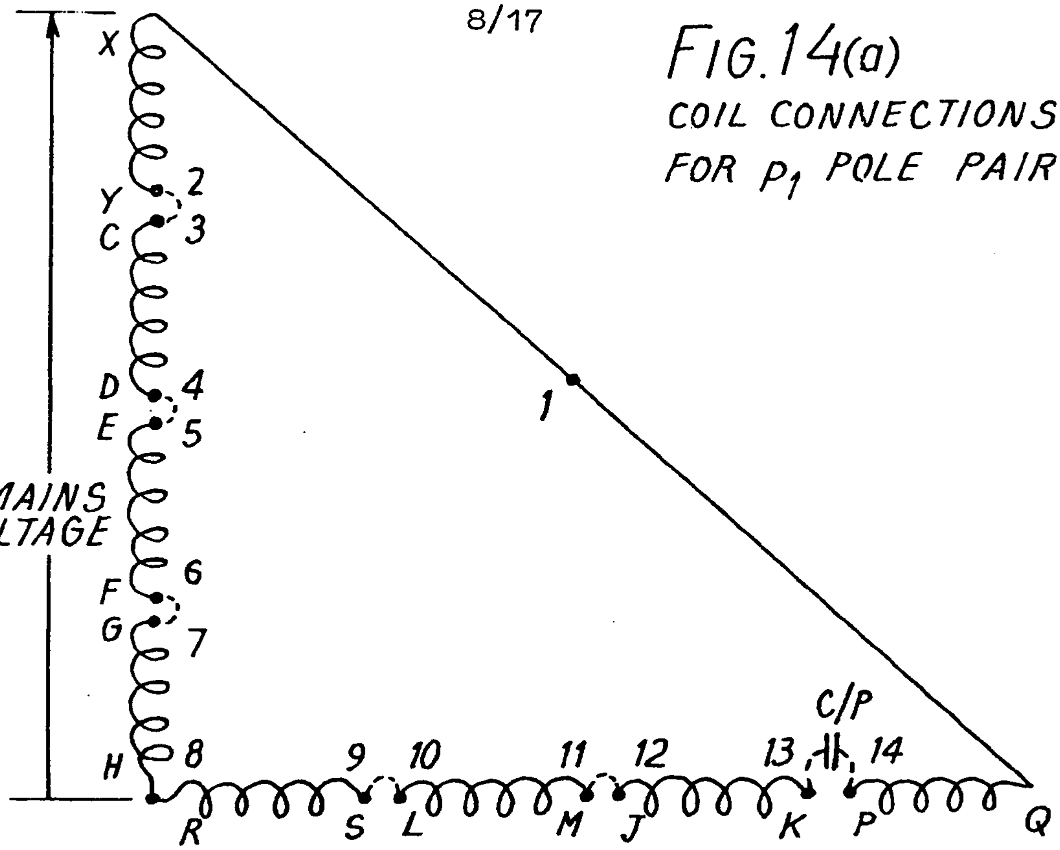


FIG. 14(a)
COIL CONNECTIONS FOR P_1 POLE PAIRS

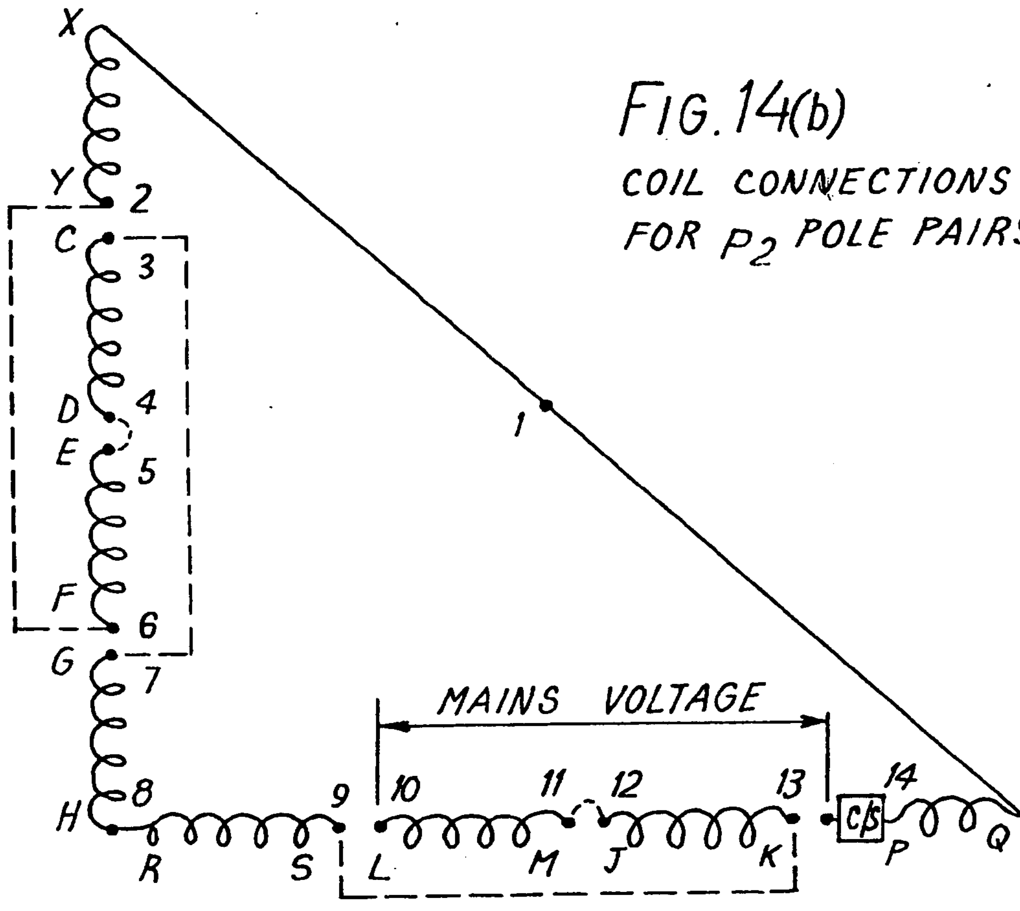
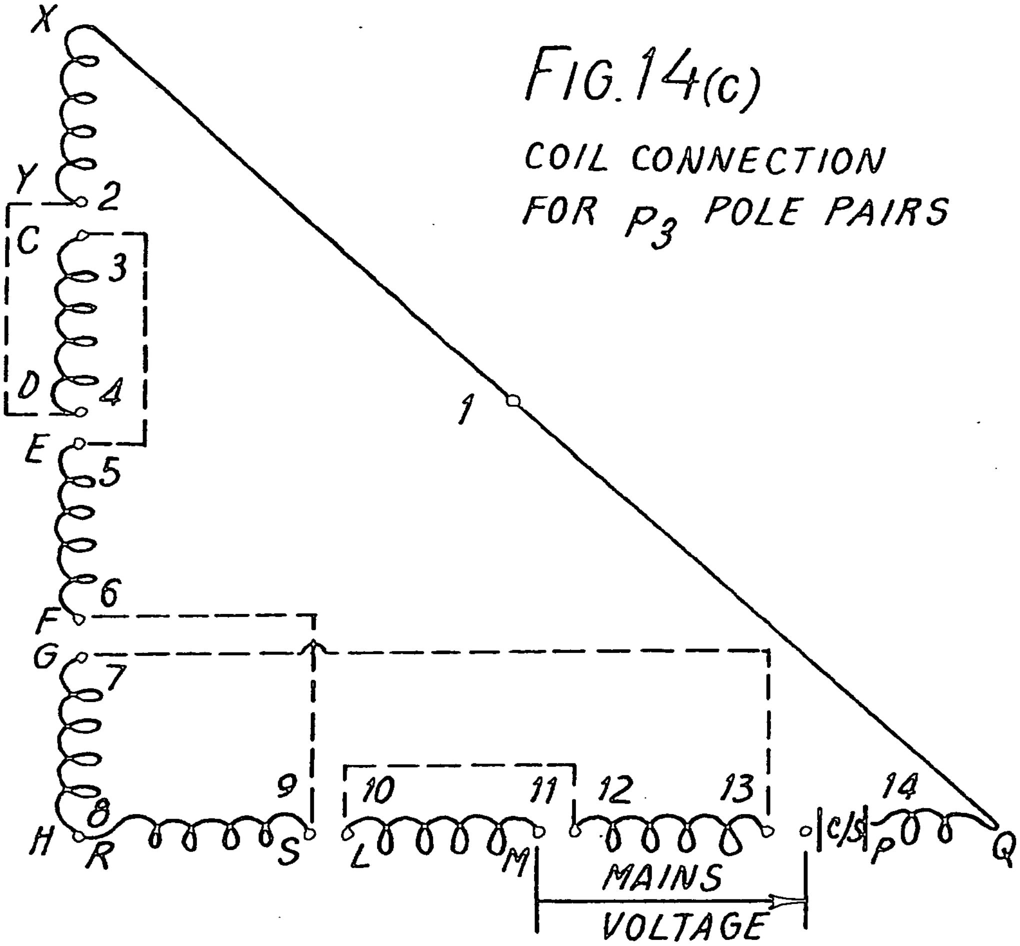


FIG. 14(b)
COIL CONNECTIONS FOR P_2 POLE PAIRS

FIG. 14(c)

COIL CONNECTION
FOR P_3 POLE PAIRS



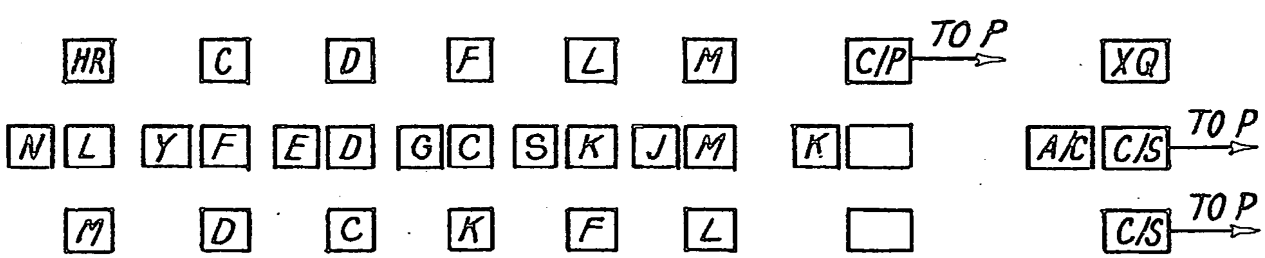


FIG. 14(d) SWITCH CIRCUIT FOR THE 3 SPEED MOTOR

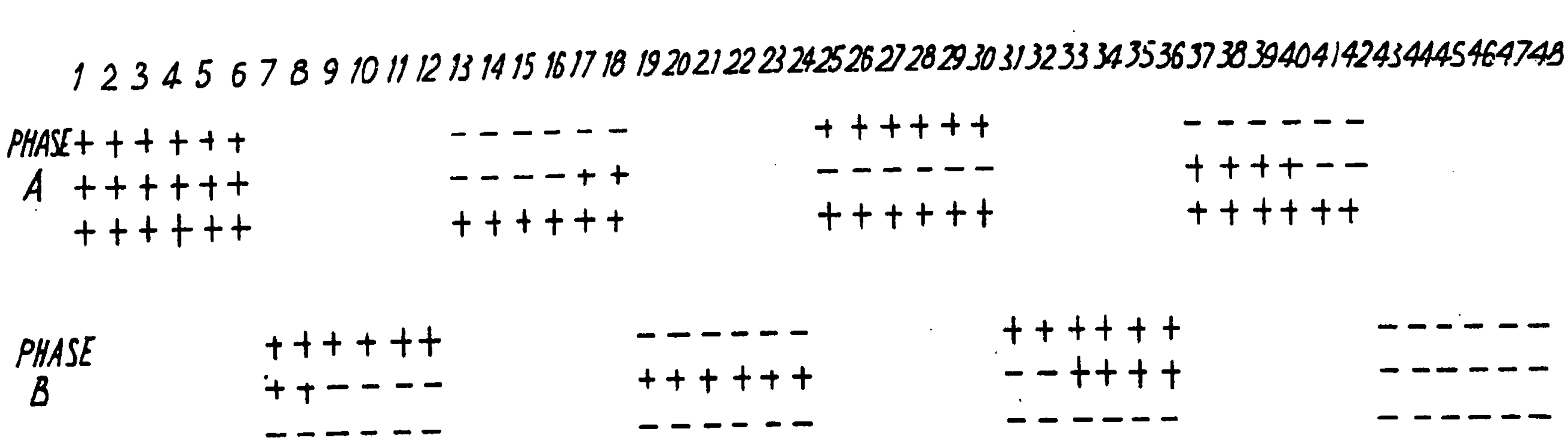


FIG 15(a)

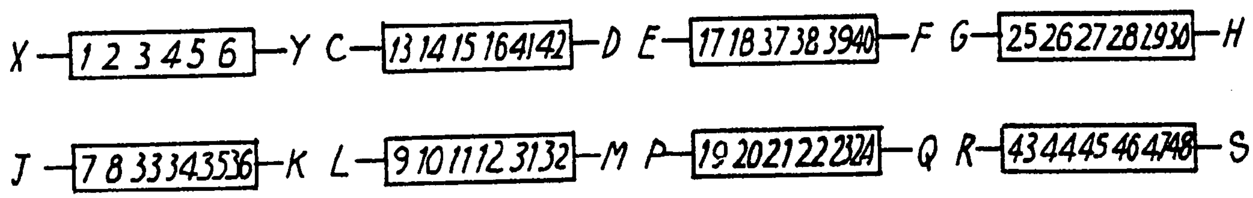


FIG. 15(b)

GROUPING OF COILS

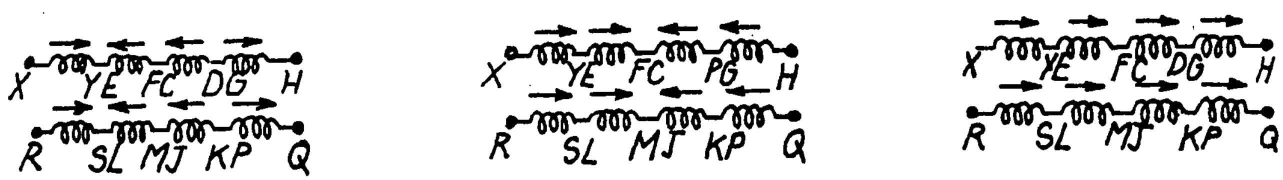


FIG. 15 (c)

COIL SEQUENCE

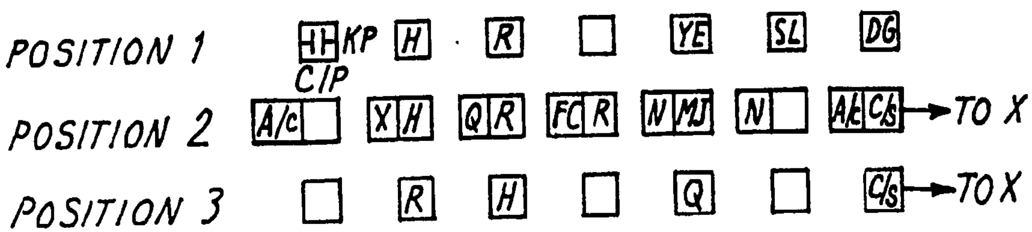


FIG. 15(d)

SWITCHING CONNECTIONS

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
PHASE A		+	+	+				−	−	−				+	+	+				−	−	−				+	+	+				−	−	−				6 POLE
		+	+	+				+	+	+				−	−	−				+	+	+				+	+	+				−	−	−				4 POLE
PHASE B					+	+	+				−	−	−				+	+	+				−	−	−				+	+	+				−	−	−	6 POLE
					+	+	+				−	−	−				−	−	−				+	+	+				−	−	−				−	−	−	4 POLE

FIG.16(a) CONDUCTOR DISTRIBUTION

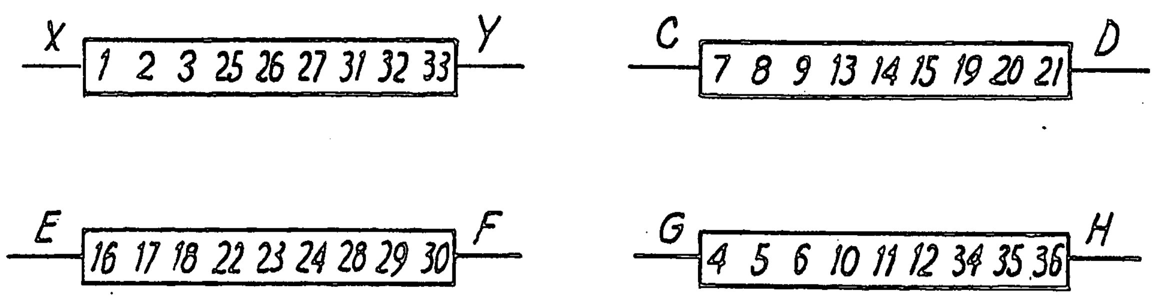


FIG.16(b) COIL GROUPINGS

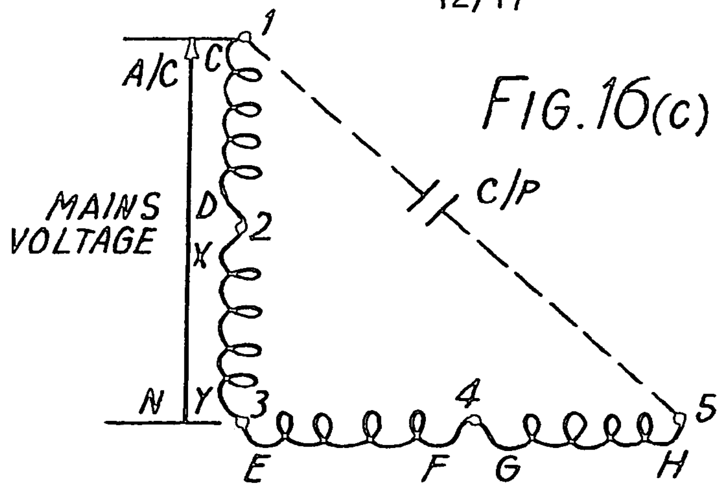


FIG. 16(c) COIL CONNECTIONS FOR P_1 POLE PAIRS

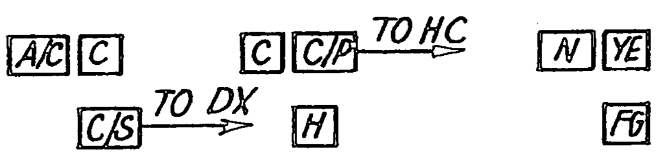


FIG. 16(d) SWITCH CIRCUIT CORRESPONDING TO FIG 16(c)

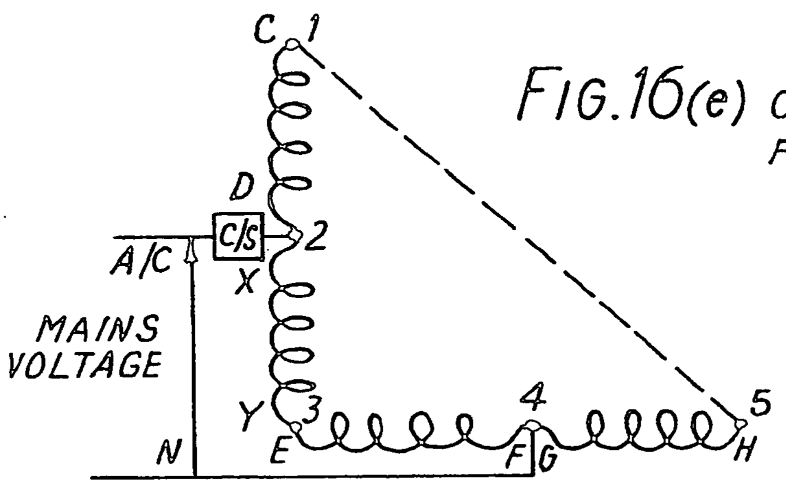


FIG. 16(e) COIL CONNECTIONS FOR P_2 POLE PAIRS

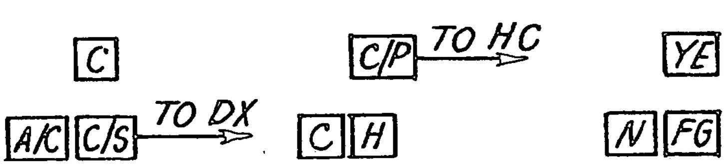


FIG. 16(f) SWITCH CIRCUIT CORRESPONDING TO FIG 16(e)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

A A A B B B -A -A -A -B -B -B A A A B B B -A -A -A -B -B -B

FIG.17(a) TOP LAYER COIL DISTRIBUTION UNMODULATED 4-POLE STATOR

A A A B B B -A -A -A B B B -A -A -A -B B B A A A -B -B -B

FIG.17(b) MODULATED COIL DISTRIBUTION

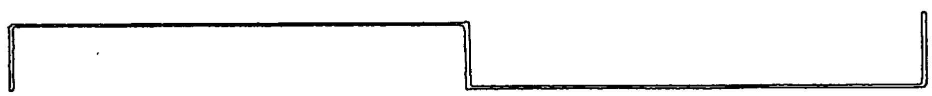


FIG.17(c) MODULATING WAVE FOR PHASE A

FIG.17(d) MODULATING WAVE FOR PHASE B

FIG.17(e) MODULATING WAVE FOR PHASE B

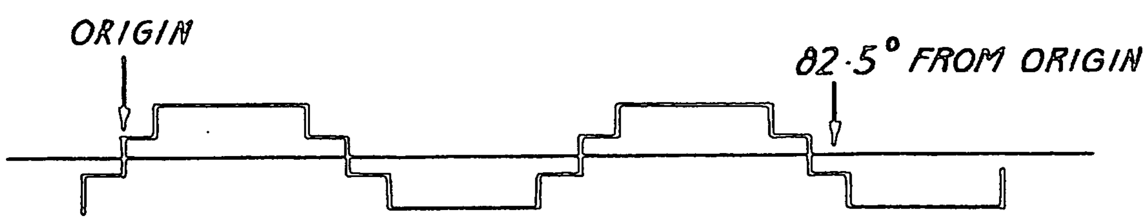


FIG.17(f) M.M.F. FOR THE TOP LAYER OF PHASE A

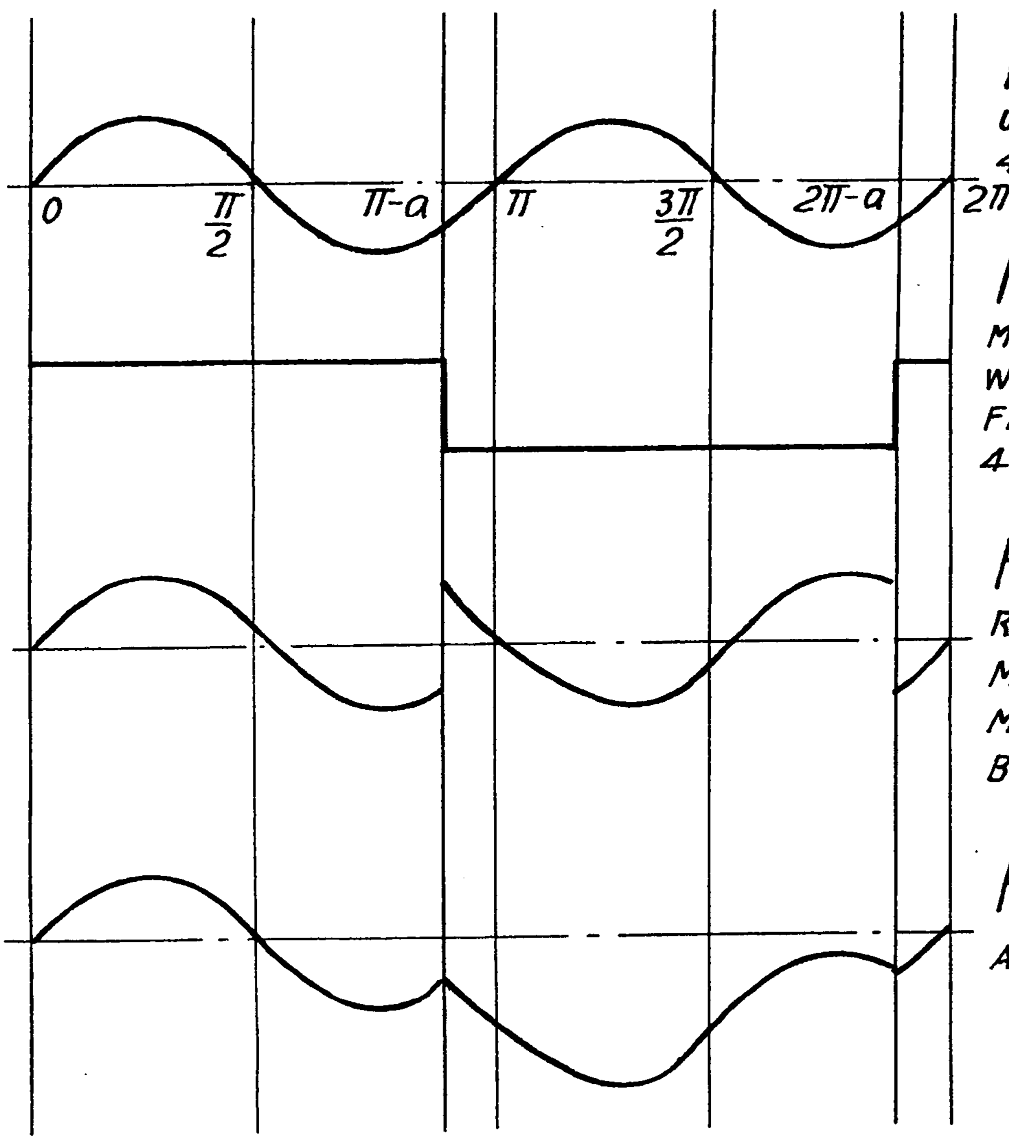


FIG.18(a)
UNMODULATED 4 POLE M.M.F.

FIG.18(b)
MODULATING WAVE DISPLACED FROM THE 4 POLE M.M.F.

FIG.18(c)
RESULTANT M.M.F. AFTER MODULATION BY (b)

FIG.18(d)
ACTUAL M.M.F.

2031660

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36

A A A A B B B B B -A-A-A-A-A-B-B-B-B A A A A B B B B B-A-A-A-A-A-B-B-B-B

FIG. 19(a) TOP LAYER COIL DISTRIBUTION OF AN UNMODULATED 4 POLE STATOR WITH 36 SLOTS

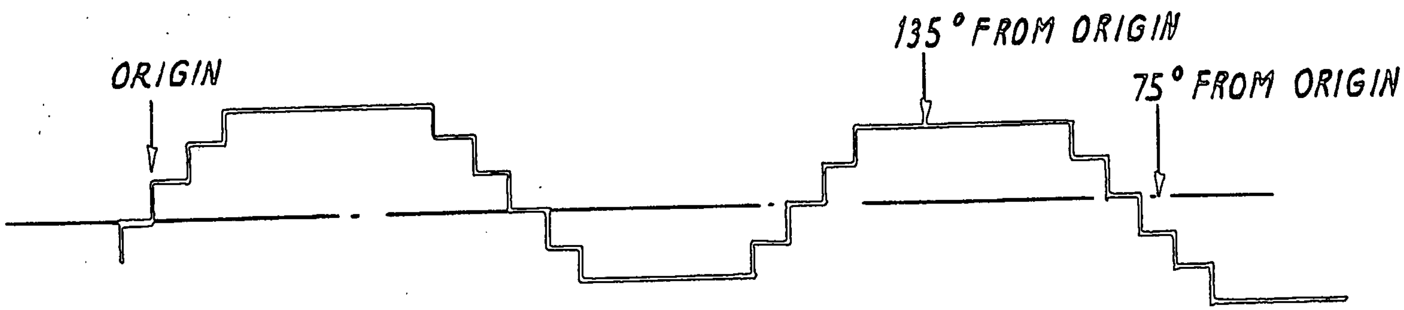


FIG. 19(b) M.M.F. FOR THE TOP LAYER OF PHASE A

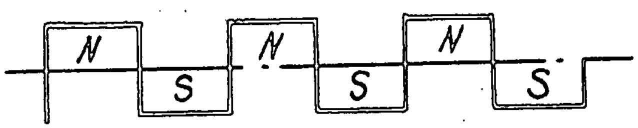


FIG. 20(a) UNMODULATED POLES

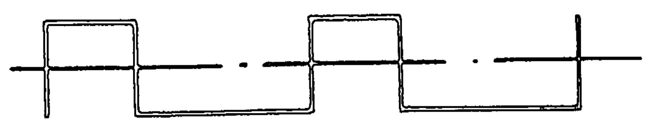


FIG. 20(b) MODULATING WAVES

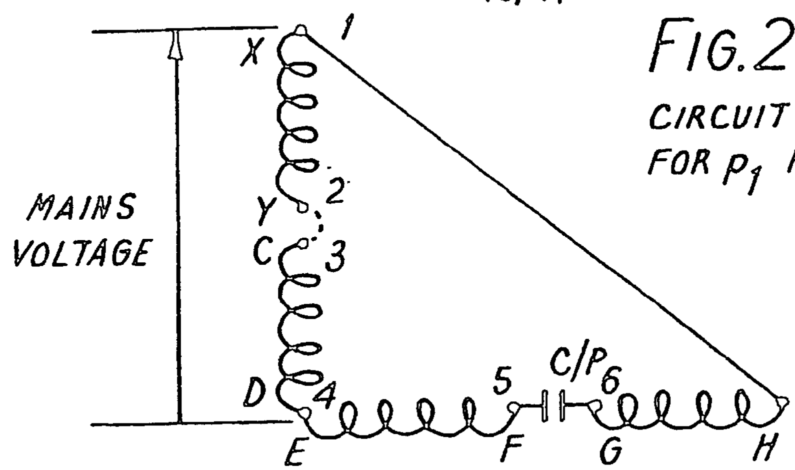


FIG. 21(a)
CIRCUIT CONNECTIONS FOR p_1 POLE PAIRS

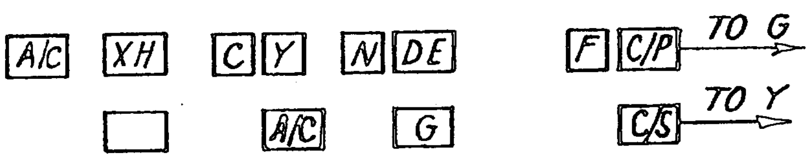


FIG. 21(b) SWITCH CIRCUIT CORRESPONDING TO FIG. 21(a)

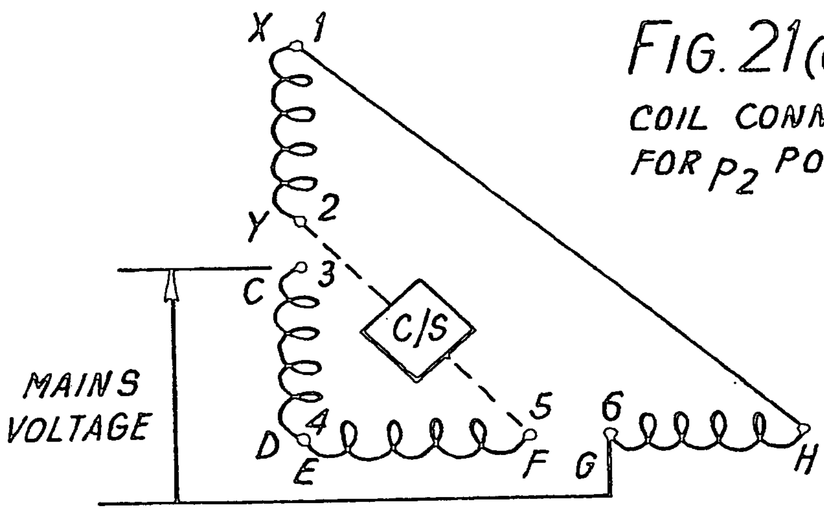


FIG. 21(c)
COIL CONNECTIONS FOR p_2 POLE PAIRS

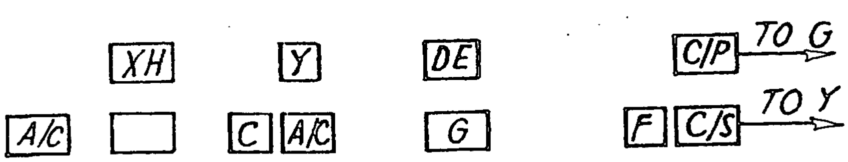


FIG. 21(d) SWITCH CIRCUIT CORRESPONDING TO FIG. 21 (c)

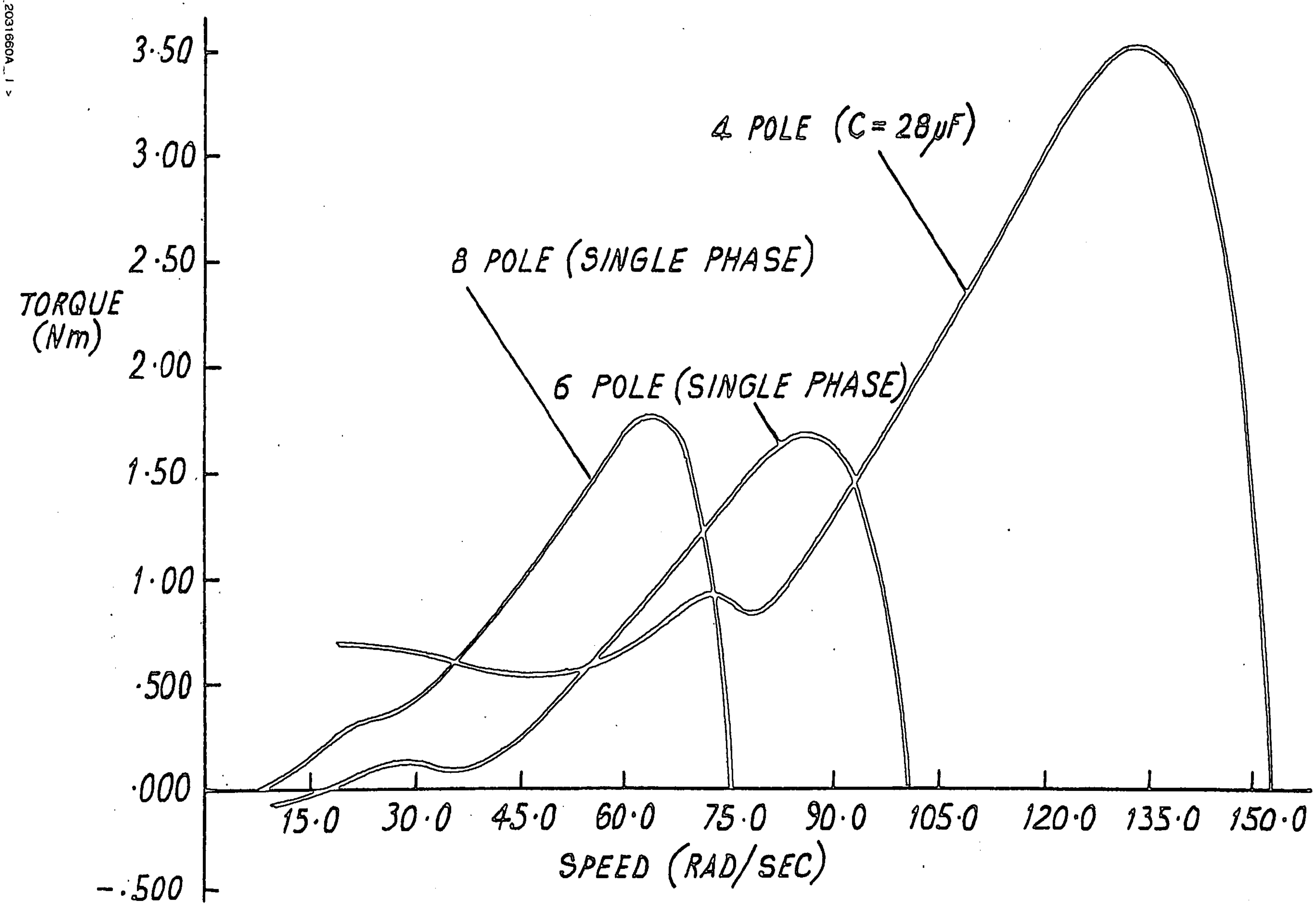


FIG. 22 TORQUE / SPEED CHARACTERISTIC OF THE 4/6/8 POLE MOTOR

SPECIFICATION

Induction electrical machines

This invention relates to induction electrical machines, and more particularly to those in which the number of poles can be changed, for example to produce different motor speeds.

Pole-changing induction motors, providing two or three alternative pole numbers, and corresponding running speeds in reverse ratio to the pole-numbers, are well-known and widely used in practice. Best known are motors employing a Dahlander winding. However, a new method called pole amplitude modulation (P.A.M.) has been devised and developed successfully in recent years to provide a step change in the number of poles and consequently in the speeds of the motor; see for example U.K. Patent Specification 900600. However, there are several difficulties in normal P.A.M. techniques when applied to small single-phase induction motors.

In British Patent 966576, in order to start and run the motor at the desired pole number, it is required to wind the machine as a three-phase motor. When the machine runs up to speed, one of the three phase-windings (which is connected to the supply via a capacitor) is open-circuited and the motor runs as a pure single-phase machine. Alternatively, the machine can be wound as a three-phase motor and run as a permanent capacitor single phase motor. However, as can be shown mathematically, the principles of P.A.M. cannot be applied satisfactorily to a true two-phase machine (which a permanent capacitor motor resembles), and the harmonic content of such motors would be high. Broadway in Patent Specification No. 1267924 applied the principle of P.A.M. to single-phase motors with concentric coils using an auxiliary winding for starting, but he pointed out that the harmonic content in his motor was rather high and he had to arrange his windings sinusoidally on the stator. Such a compromise however, is difficult to achieve if one requires more than two speeds from the motor. Moreover, the starting torque for such single-phase P.A.M. motors would be low owing to the large harmonic content and they would not be suitable for driving compressors and other loads which require a reasonable starting torque. In addition, this method requires either symmetrical or assymmetrical modulation to the winding, depending on the ratio of modulated pole number to the unmodulated pole number. This is a rather inconvenient restriction for motors having more than two speeds.

If a single-phase P.A.M. motor which is wound as a three-phase motor is to be run at a pole number which is three or a multiple of three, the principles of P.A.M. as described in British Patent 900600cannot be applied directly. The principle of assymmetrical winding as described in British Patent 926101 can be employed, but this obviously would involve complicated switching. Alternatively, one could distribute the winding non-uniformly as described in British Patent 986384, but this requires a large number of slots, which is not suitable for small single-phase motors.

Krishnamurthy and Rajaraman, in Proceedings of the Institution of Electrical Engineers, Vol. 112, No. 6, described an application of P.A.M. to a double layer (i.e. lap wound) motor, whereby they start and run the motor at a particular pole number as a two-phase motor, and then as a single-phase motor after modulation to give a different pole number. However, since they failed to realise that the two phases of the original motor after modulation could be regarded as a single winding, they were accordingly restricted in their winding arrangement and had to employ coil omission to achieve a reasonable harmonic content. As a result, the winding factor suffers considerably. Moreover, by regarding phases A and B of a two-phase motor as two separate entities (even though they are joined together after modulation), it was assumed that the modulating waves for phases A and B had to be exactly 90 degrees apart per pole pair change after modulation, and it was therefore though impossible to apply this method to obtain a modulated six pole machine from an unmodulated four pole machine, because the conductors of phase A occupy both positions at which the modulating waves for phases A and B, respectively, are supposed to start. In order to minimise the harmonic content at the modulated pole number, Krishnamurthy proposed pre-grouping the conductors at the unmodulated pole number, but this inevitably introduced a large harmonic content at the unmodulated pole number. The winding factor also decreases owing to the irregularities introduced. To overcome the difficulties of certain pole combinations, Krishnamurthy proposed using assymmetrical modulation, but this requires the omission of coils and the harmonic content is high. Krishnamurthy has also proposed a method called total modulation wherein phases A and B are modulated by two modulating waves which are not 90° apart, but again the harmonic content is high. In the description that follows and in the mathematical analysis at the end of this specification, it can be seen that these practices and limitations of the prior art do not apply in the present invention.

In a first aspect this invention provides an induction electrical machine having a ferromagnetic core with a number of slots, a double layer winding occupying those slots, the winding comprising two phase-windings for two-phase operation at a first pole number, the top layer of the double layer winding having the conductors assigned to s/4p (or an integral number adjacent thereto if it is a non-integer) successive slots for each pole of each of the two phase-windings (wherein s is the number of stator slots and p is the number of pole pairs), the coil pitch being selected so as to produce acceptable harmonics for the two-phase operation, and switching means for reconnecting coils or groups of coils of the two phase-windings in two different ways according to the method of pole amplitude nodulation to convert them into a single phase winding at each of respective second and third pole numbers, wherein the positions of both modulating waves producing the second pole number are different from those producing the third pole number.

In a second aspect this invention provides an

induction electrical machine having a ferromagnetic core with a number of slots, a double layer winding occupying those slots, the winding comprising two phase-windings for two-phase operation at a first pole number, the top layer of the double layer winding having the conductors assigned to s/4p (or an integral number adjacent thereto if it is a non-integer) successive slots for each pole of each of the two phase-windings (wherein s is the number of stator slots and p is the number of pole pairs), the coil pitch being selected so as to produce acceptable harmonics for the two-phase operation, and switching means for reconnecting coils or groups of coils of the two phase-windings according to the method of pole amplitude modulation to convert them into a single phase winding at a second pole number, the modulating waves applied to the two phase-windings being mutually displaced around the machine axis by greater or less than 90° measured on the scale $k\theta$ wherein k is the number of modulating pole pairs in one revolution and θ is mechanical degrees around the machine axis.

In a third aspect this invention provides an induction electrical machine having a ferromagnetic core with a number of slots, a double layer winding occupying those slots, the winding comprising two phase-windings for two-phase operation at a first pole number, the top layer of the double layer winding having the conductors assigned to s/4p (or an integral number adjacent thereto if it is a non-integer) successive slots for each pole of each of the two phase-windings (wherein s is the number of stator slots and p is the number of pole pairs), the coil pitch being selected so as to produce acceptable harmonics for the two-phase operation, and switching means for reconnecting coils or groups of coils of the two phase-windings to convert them into a single phase winding at a second pole number, such that the top layer of the double layer winding has the conductors assigned to $s/2p_2$ (or an integral number adjacent thereto if it is a non-integer) successive slots for each pole of the second pole number (wherein s is the number of stator slots and p_2 is the number of pole pairs at the second pole number), except that one or more coils providing conductors in the top layer adjacent one end of each of alternate $s/2p_2$ groups of conductors are reversed.

In a fourth aspect this invention provides an induction electrical machine having a ferromagnetic core with a number of slots, a double layer winding occupying those slots, the winding comprising two phase-windings for two-phase operation at a first pole number, the top layer of the double layer winding having the conductors assigned to s/4p (or an integral number adjacent thereto if it is a non-integer) successive slots for each pole of each of the two phase-windings (wherein s is the number of stator slots and p is the number of pole pairs), the coil pitch being selected so as to produce acceptable harmonics for the two-phase operation, and switching means for reconnecting coils or groups of coils of the two-phase windings, according to a method of pole amplitude modulation in which separate pole amplitude modulating waves are applied to the phase-windings, the two modulating waves being displaced from each other around the machine axis by less than 180°, to convert the two phase-windings into a single phase-winding at a second pole number. Preferably the switching means provides two alternative reconnections giving single phase-windings at respectively second and third pole numbers of which one is above and one is below the first pole number.

In some cases the number of effective conductors in one phase winding can be different from those of the other phase winding. For the two-phase operation at the first pole number, the phase-winding which is connected to the supply via a capacitor can be open-circuited after the motor runs up to speed. The motor then operates in the well-known capacitor start-induction run regime at the unmodulated pole number. Alternatively, the value of capacitance which is connected between the supply and one of the phase-windings can be changed, for example by switching, after the motor runs up to speed. The motor then operates in the well-known capacitance start-capacitor run regime at the unmodulated pole number. This invention is particularly useful for producing motors having three alternative pole numbers. Those aspects of the invention which apply to motors providing two alternative pole numbers can also be embodied in motors providing three alternative pole numbers. It is preferred in most cases that the two-phase operation is at the lowest or the highest of three alternative pole numbers; being for example the highest pole number where the anticipated use for the motor will require a relatively high starting torque, as in driving some compressors and pumps, but otherwise being the lowest pole number where the highest current is drawn at the highest motor speeds (i.e. at the lowest pole number).

In order that the invention may be more clearly understood, it will be more particularly described with reference to the accompanying drawings.

The method of designing a stator embodying the present invention can be generally described in the following manner.

Let s be the number of slots of the stator. The motor is required to start as a two-phase machine at p_1 pole pairs, and run as a two-phase machine at p_1 pole pairs or as a single phase machine at either p_2 or p_3 pole pairs. It is obvious that for p_1, p_2 and p_3 pole pairs, there should be $s/2p_1$, $s/2p_2$ and $s/2p_3$ slots per pole respectively. In other words, slot number 1 to slot number s/2p (or the nearest integral number below or above s/2p) belongs to the first pole, while slot number s/2p + 1 to slot number 2s/2p belongs to the second pole, and so forth 2p times around the periphery of the complete stator. (p can take up the value of p_1 or p_2 or p_3). Consequently one can assign the conductors to the slots in this way for each of the three different pole numbers.

To begin with, the conductor layout for the two-phase operation is determined. Since each of the two phase-windings will have p pole pairs (where p is the two-phase pole pair number) successive conductors in the top layer of one phase-winding will occupy s/4p slots (or the nearest integral number above or below it if it is a non-integer). For example, taking a 24-slot stator requiring 4, 6 and 8 poles, of

which the 4-pole arrangement is to be at 2-phase; s/4p = 3 slots. Thus the first three slots carry in the top layer conductors of phase A, the next three conductors of phase B, the next three conductors of phase A, and so forth. This can be represented as

+A, +A, +A, +B, +B, +B,
−A, −A, −A, −B, −B, −B

and so forth around the stator. The disposition of the conductors in the lower layer is of course determined from the top layer by the choice of coil pitch, the bottom layer being the same as the top layer but displaced by the coil pitch and of opposite sign. This is chosen to suit individual motor requirements, for example whether it is to be used for a constant torque or falling torque application, and in particular the choice of coil pitch will be influenced by the harmonic content and the need to avoid interfering harmonics during 2-phase operation (which of course includes starting the motor and running it up to speed). Also the coil pitch should be selected so as to provide as far as possible a suitably shaped magnetomotive force (m.m.f.) and a ratio of flux densities (B) suited to the duties of the machine at the alternative pole numbers, so that the choice of coil pitch may represent a compromise between conflicting requirements. However, since it may be difficult or impossible in some cases to find a suitable compromise with the requirements of both of the other two pole numbers, the harmonic content of one or both of these alternative windings can be modified in the manner described later.

In the example given above, a coil pitch of 4 slots has been selected, and the full layout of the conductors for the 2-phase operation is as shown in Fig. 1(a). (The numbering of the slots is of course entirely arbitrary. The minus sign indicates current flowing in that conductor in the opposite direction to the current in a conductor not having the minus sign.) The direction of current flow in the two layers can be represented approximately by a square wave pattern as in Fig. 1(b), the peaks representing current flowing in one direction and the troughs representing current flowing in the opposite direction. Since this is a 2-phase system, the fundamental component of the wave will travel continuously longitudinally, so that Fig. 1(b) represents the situation at only one instant (namely when the currents in phases A and B are equal).

Considering now the arrangement of conductors for the second and third pole numbers, in this example p = 3 and 4 respectively: for p = 3, s/2p = 4 slots; and for p = 4, s/2p = 3 slots. The conductor layout of Fig. 1(a) which has been determined for the 2-phase operation can only be modified by changing the pattern of current flow in the top layer (since it is not possible to physically move the coils or alter the coil pitch, and we are not concerned with the possibility of coil omission). Accordingly for p = 3, the first four slots can be assigned to one pole, the next four to the next pole, and so on. The resulting layout is as shown in Fig. 1(c), represented by a square wave pattern as in Fig. 1(d). The pattern for p = 4 can be similarly chosen, as shown in Figs. 1(e) and 1 (f). The square wave patterns of Figs. 1(d) and 1(f) will of course be stationary longitudinally, although their amplitude will vary with time.

The harmonic content for the three conductor arrangements of Figs. 1(a), 1(c) and 1(e) are shown in Table 1A.

TABLE 1A

Coil pitch: 4 slots		
Harmonic content for 4 poles	4 poles	100.0%
unmodulated (Phase A)	20 poles	5.4%
Conductor grouping	28 poles	3.8%
phase A and phase B	44 poles	9.1%
3-3-3-3	52 poles	7.7%
	92 poles	4.3%
Winding factor: 0.789	100 poles	4.0%
Harmonic content for 6 poles	6 poles	100.0%
modulated. (Phases A and B)	18 poles	13.8%
Conductor grouping	30 poles	8.3%
4-4-4-4-4-4	42 poles	14.3%
	54 poles	11.1%
	66 poles	3.8%
	78 poles	3.2%
	90 poles	6.7%
	102 poles	5.9%
	114 poles	2.2%
	126 poles	2.0%
	138 poles	4.3%
Winding factor: 0.653	150 poles	4.0%
Ratio of flux densities B6/B4 0.91		
Harmonic content for 8 poles	8 poles	100.0%
modulated. (Phases A and B)	40 poles	20.0%
Conductor grouping	56 poles	14.3%

3-3-3-3-3-3-3-3	88 poles	9.1%
	104 poles	7.7%
	136 poles	5.9%
	152 poles	5.3%
	184 poles	4.3%
Winding factor: 0.577	200 poles	4.0%

Ratio of flux densities B8/B4 1.37

It will be seen that the third harmonic for the 6 pole arrangement is quite high, and will be particularly troublesome since it is too near the fundamental. The higher harmonics in the 6- and 8-pole configurations are mainly due to the small number of slots per pole (a 24-slot stator being a very small number of slots per pole for 6 or 8 poles and one of the most difficult cases to deal with in practice), and they should decrease for stators with higher numbers of slots as the number of slots per pole increases. It can be shown theoretically that in single phase windings the third harmonic is the most troublesome, and generally one would try and choose a coil pitch near to 2/3 pole pitch (or a multiple thereof) in order to eliminate or minimise the third harmonic. However this may not be possible in view of the requirements of the other pole numbers.

In the present example, the selected coil pitch of 4 slots is equivalent to 2/3 of the pole pitch in the 2-phase 4-pole arrangement and equivalent to 4/3 of the pole pitch in the single-phase 8-pole arrangement, so that the third harmonic is eliminated in both cases. However, in the 6-pole arrangement the coil-pitch is the same as the pole pitch, which explains the high third harmonic in Table 1A. This can be improved by reversing one coil at one end of alternate poles around the stator. By "reversing a coil" we mean reversing the current flow in the coil with respect to the current flow indicated in Fig. 1(c). Thus, the current flow can be reversed for the top layer conductors in slot Nos. 1, 9 and 17, being the first conductor in each of the first, third and fifth poles. The corresponding conductors in the bottom layer (being the other half of the coils concerned) will likewise have their current reversed. The resulting conductor distribution is shown in Fig. 1(g) and its harmonic content is shown in Table 1(b).

TABLE 1B

Harmonic content for 6 poles	6 poles	100.0%
modulated. (Phases A and B)	18 poles	5.7%
Conductor grouping	30 poles	3.4%
3-5-3-5-3-5	42 poles	14.3%
	54 poles	11.1%
	66 poles	1.6%
	90 poles	6.7%
	102 poles	5.9%
	138 poles	4.3%
Winding factor: 0.604	150 poles	4.0%

Ratio of flux densities B6/B4 0.98

From this Table it will be seen that the third harmonic has now been greatly reduced. From Fig. 1(g) it will be seen that alternate s/2p groups of conductors in the top layer have been reduced by one slot and the other groups there increased by one slot, so that the effective pole pitch for the top layer becomes respectively 3/4 and 5/4 of the normal pole pitch. Ideally, of course, these figures should be 2/3 and 4/3 respectively, but obviously this cannot be achieved where the normal pole pitch is four slots. Where the normal pole pitch is not divisible by three, as in this case, the pole reduction should be to the nearest slot above or below 2/3 normal pole pitch, preferably the nearest above it, as in this case. Although the third harmonic is usually the most troublesome in single phase windings; where it is not, any other troublesome harmonic could in theory be reduced or eliminated by the same procedure. In general the nth harmonic is reduced or eliminated by coil reversal to reduce alternate pole pitches in the top layer to $(n - 1)/n$ of the normal pole pitch.

It is possible that in some cases s when divided by each of $2p_1$, $2p_2$ and $2p_3$ does not give an integer. In this case, some of the poles would contain more slots than the others, and it is necessary for the designer to sort out the best compromise arrangement. One of the existing techniques for doing this is a graphical method whereby one allots an e.m.f. vector to each conductor. By joining the e.m.f. vectors of all conductors in series, an experienced designer should be able to pick up the best arrangement. Another existing technique would be to use a computer to analyse the m.m.f.'s of various possible arrangements.

We will consider a numerical example in this category in which $s = 32$, $p_1 = 2$, $p_2 = 3$ and $p_3 = 4$, and the 2-phase operation is at $p_1 = 2$. It is clear that s is not divisible by $2p_2$. For the 6-pole situation ($p_2 = 3$) one could divide s into 6 sections with five or six slots per section. One of the arrangements is

5 5 6 5 5 6

In other words, there are 5 slots belonging to the 1st pole, followed by another 5 slots in the second pole, and 6 slots in the third pole and so forth. Another arrangement would be

5 5 6 6 5 5

In this case, there would be 5 slots for the first two poles, followed by 6 slots for the third and fourth poles, and the last two poles will have 5 slots. Using the same technique as described above, three different square waves can be drawn and conductors assigned to appropriate slots and a suitable coil pitch selected (5 slots in this case). The harmonic analysis of the resultant conductor distribution for the two alternative arrangements for $p_2 = 3$ is shown in Table 2.

TABLE 2

Coil pitch: 5 slots		
Harmonic content for 4 poles	4 poles	100.0%
unmodulated. (Phase A)	12 poles	2.7%
Conductor grouping	20 poles	5.5%
phase A 4-4-4-4	28 poles	1.9%
phase B 4-4-4-4	44 poles	2.5%
	60 poles	6.7%
Winding factor: 0.753	68 poles	5.9%
Harmonic content for 6 poles	2 poles	8.9%
modulated. (Phases A and B)	4 poles	20.8%
Conductor grouping	6 poles	100.0%
5-5-6-6-5-5	8 poles	12.9%
	16 poles	3.8%
	18 poles	9.2%
	20 poles	5.8%
	30 poles	2.1%
	32 poles	3.8%
	34 poles	1.8%
	44 poles	2.6%
	46 poles	3.6%
	56 poles	1.8%
	58 poles	10.3%
	70 poles	8.6%
	82 poles	2.0%
	122 poles	4.9%
Winding factor: 0.622	134 poles	4.5%
B6/B4 0.91		
Harmonic content for 6 poles	2 poles	15.8%
modulated. (Phases A and B)	6 poles	100.0%
Conductor grouping	10 poles	4.8%
5-5-6-5-5-6	18 poles	10.8%
	22 poles	3.3%
	30 poles	3.7%
	34 poles	3.3%
	42 poles	1.7%
	46 poles	4.2%
	58 poles	10.3%
	70 poles	8.6%
	82 poles	2.4%
	110 poles	1.8%
	122 poles	4.9%
Winding factor: 0.635	134 poles	4.5%
B6/B4 0.89		
Harmonic content for 8 poles	8 poles	100.0%
modulated. (Phases A and B)	24 poles	5.7%
Conductor grouping	40 poles	3.4%
4-4-4-4-4-4-4-4	56 poles	14.3%
	72 poles	11.1%
	88 poles	1.6%
	120 poles	6.7%
	136 poles	5.9%
	184 poles	4.3%
Winding factor: 0.604	200 poles	4.0%
B8/B4 1.248		

It will be seen that the $p_2 = 3$ arrangement

5-5-6-6-5-5

gives a somewhat lower third harmonic.

It is possible in some cases that although s/2p is an integer, s/4p is not (p being the 2-phase pole pair number). In such a case phase windings A and B would each contribute a different number of conductors for any given pole, but the overall pattern in each phase-winding would be the same. A particular example should make this clear.

Consider a double layer winding with $s = 36$, $p_1 = 2$, $p_2 = 3$ and $p_3 = 4$, and p_1 is the 2-phase pole pair number. It is clear that $s/2p_1$ (=9) is not divisible by 2. In this case, phase A would have 4 slots in the 1st pole and 5 slots in the second pole, while phase B would have 5 slots in the first pole and 4 slots in the second pole. The conductor distribution for the top layer of this machine in half of the periphery is thus

A A A A B B B B B −A −A −A −A −A − B −B −B −B

This will be repeated in the second half of the stator periphery. A 5-slot coil pitch is selected. The harmonic analysis of an arrangement of this type is shown in Table 3.

TABLE 3

Coil pitch: 5 slots		
Harmonic content for 4 poles	4 poles	100.0%
unmodulated. (Phase A)	8 poles	8.0%
Conductor grouping	12 poles	7.1%
phase A 4-5-4-5	20 poles	4.7%
phase B 5-4-5-4	24 poles	2.3%
Winding factor: 0.688	36 poles	1.8%
Harmonic content for 6 poles	6 poles	100.0%
modulated. (Phases A and B)	18 poles	8.9%
Conductor grouping	54 poles	3.0%
6-6-6-6-6-6	66 poles	9.1%
	78 poles	7.7%
	90 poles	1.8%
	138 poles	4.3%
Winding factor: 0.622	150 poles	4.0%
B6/B4 0.83		
Harmonic content for 8 poles	8 poles	100.0%
modulated (Phases A and B)	16 poles	3.2%
Conductor grouping	24 poles	10.2%
5-4-5-4-5-4-5-4	32 poles	3.7%
	40 poles	3.0%
Winding factor: 0.630	48 poles	5.1%
B8/B4 1.09		

The procedure of the present invention can not only be applied to windings having three pole numbers in which the 2-phase arrangement is at the lowest pole number, but also to windings in which the 2-phase arrangement is at the highest or the middle pole number. Obviously, if the method can produce windings with three alternative pole numbers, it can produce windings with just two alternative pole numbers, one of them being a 2-phase arrangement. In principle the method could also be applied to produce windings with more than three alternative pole numbers, but even though the problems of finding a suitable compromise for the greater number of possibly conflicting requirements might be overcome in many cases, the switching requirements would become increasingly complicated, and in practice more than three alternative pole numbers are unlikely to be employed.

The situation where the 2-phase pole number is the middle one of three pole numbers is, of course, also found in prior art P.A.M. proposals, notably that of Krishnamurthy and Rajaraman noted above. However the art of Krishnamurthy and Rajaraman generally leads to three speed motors in which the modulated pole numbers are an equal number of poles above and below the unmodulated pole number. In the present invention this restriction does not exist. Moreover, the greater freedom in the present design approach can lead to better results than those obtained by the simple application of conventional P.A.M. procedures. To illustrate this we will in the next example apply the procedure of the present invention to the situation faced by Krishnamurthy and Rajaraman in the above cited prior art. This required a 36-slot stator with a winding producing 4 poles, 6 poles and 8 poles, with 2-phase operation in the 6-pole condition.

The procedure as described above was used to assign conductors into slots at the three different pole numbers and select a suitable coil pitch (in this case 6 slots). The resulting conductor arrangements are shown in Figs. 2(a), (b) and (c), and the harmonic analysis in Table 4.

TABLE 4

Coil pitch: 6 slots		
Harmonic content for 6 poles	6 poles	100.0%
unmodulated. (Phase A)	18 poles	12.2%
Conductor grouping	30 poles	5.4%
phase A and phase B	42 poles	3.8%
3-3-3-3-3-3	54 poles	4.1%
	66 poles	9.1%
	78 poles	7.7%
	90 poles	2.4%
Winding factor: 0.911	102 poles	1.6%
Harmonic content for 4 poles	4 poles	100.0%
modulated. (Phases A and B)	20 poles	4.5%
Conductor grouping	28 poles	2.6%
9-9-9-9	44 poles	1.7%
	52 poles	1.7%
	68 poles	5.9%
	76 poles	5.3%
Winding factor: 0.554	140 poles	2.9%
B4/B6 1.1		
Harmonic content for 8 poles	8 poles	100.0%
modulated (Phase A in series with	16 poles	9.2%
phase B)	32 poles	5.7%
Conductor grouping	40 poles	4.5%
4-5-4-5-4-5-4-5	56 poles	2.6%
	64 poles	12.5%
	80 poles	10.0%
	88 poles	1.7%
	104 poles	1.7%
	112 poles	1.6%
	136 poles	5.9%
Winding factor: 0.554	152 poles	5.3%
B8/B6 1.1		

In the prior art disclosure, the 2-phase 6 pole winding of Fig. 2(a) was first modulated by a square wave as shown in Fig. 2(d) for phase A and Figs. 2(e) and (f) for phase B. In Fig. 2(e) the modulating wave of phase B is 90° ahead of the modulating wave of phase A in Fig. 2(d), and produced a 4-pole m.m.f. In Fig. 2(f) the modulating wave of phase B is 90° behind the modulating wave of phase A in Fig. 2(d), and produced an 8-pole m.m.f. This was exactly in accordance with P.A.M. theory. It will be observed that the modulating wave for phase A, as in Fig. 2(d) is unchanged in both conditions, whereas the modulating wave for phase B is displaced exactly like 90° on either side of it. (This is 90° on the scale $k\theta$, where k = no. of modulating pole pairs and θ = mechanical degrees. In this instance, since $k = 1$, $k\theta$ is the same as mechanical degrees around the machine axis). The conductor arrangement and 4-pole m.m.f. resulting from modulation by the waves of Figs. 2(d) and (e) was similar to, although displaced around the stator axis from that produced by the present procedure as shown in Fig. 2(b) which corresponds to modulation of phase A and phase B windings by the square waves shown in Figs. 2(g) and (h) respectively. However, the 8-pole conductor arrangement of Krishnamurthy and Rajaraman was appreciably different from that of Fig. 2(c), and was very unsatisfactory. Krishnamurthy and Rajaraman sought to improve the situation by modifying the modulating wave to a somewhat more sinusoidal shape by the technique of coil omission and this produced a reasonable m.m.f. However, coil omission in lap-wound motors is undesirable, and th technique of the present invention produces an improved 8-pole m.m.f. from the conductor configuration shown in Fig. 2(c). This is equivalent to applying modulating square waves to phases A and B as shown in Figs. 2(i) and 2(j) respectively, but it will be seen that the modulating waves of phases A and B in Figs. 2(i) and 2(j) are both displaced from the corresponding modulation waves of Figs. 2(g) and 2(h), thereby distinguishing this result from the result obtained by the application of conventional P.A.M. methods. Such displacement of the modulating waves for the two modulated pole numbers is explained fully in the mathematical analysis at the end of this specification.

In Figs. 2(g) to (j), although the modulating waves are all at different positions, in each case the displacement between the modulating wave of phase A and that of phase B is 90° on the scale $k\theta$, which does correspond to conventional P.A.M. theory. However, this is purely fortuitous, and it is not an essential feature of the procedure of the present invention. For example, the 5-5-6-6-5-5 grouping of Table 2 can be considered as a modulation of the corresponding 4-pole grouping by modulating square waves applied to phases A and B as shown in Fig. 3. It will be seen that the displacement between the two modulating waves is 5 slots, and hence 56°15′ since

90° on the scale $k\theta$ is 8 slots. In fact, the two modulating waves should be 61.6° apart as shown later in the mathematical analysis. It will also be noted that the modulating waves are not symmetrical, since one pole of each wave occupies 17 slots, while the other pole occupies 15 slots. This again is a distinction over conventional P.A.M. This could, of course, be explained mathematically provided one considers the possibility of having unsymmetrical square waves. This is, however, a tedious task and the above modulation is in fact obtained by regarding phases A and B as a single phase after modulation.

When the stator has been wound, it is obviously necessary to provide some means for switching between the different pole numbers. Conventional rotary switches can be employed, but the switching requirement can be considerably simplified by assigning the coils into groups, each group containing coils which are switched in a similar manner for the different pole numbers. This can best be seen by setting out the top layer conductors showing the direction of current at each pole number, for example as shown in Fig. 4 which refers to the 24-slot stator winding of Fig. 1. For clarity, phase A and phase B conductors are shown separately, but this is not essential. The + and − signs are merely arbitrary designations indicating relative direction of current flow.

From the diagram of Fig. 4, it can be seen that, for example, the top conductors in slots 1, 13, 14 and 15 carry current in the same direction at all three pole numbers, and this is designated group XY in Fig. 5. By a similar process groups CD, EF, GH, JK, LM, NP and QR are found (XY is used instead of AB to avoid confusion with phase A and phase B). In interconnecting the groups for 4 poles, it is obviously necessary to connect up the groups of phase A separately from those of phase B, but for 6 poles and 8 poles there is no differentiation between the phase windings. Fig. 6 shows the interconnection of the groups. Where the designation of a group has been reversed, for example YX instead of XY, this indicates that the direction of current in the one is reversed with respect to the other. In other words the current flows in the same direction through XY in the 4 pole and 8 pole configurations and in the reverse direction through YX in the 6 pole configuration. The linear interconnection of the groups in Fig. 6 simply means that they are connected together in series, not necessarily in the order shown.

By grouping the coils in this way the switching is relatively simple, and clearly not more than 14 leads will be required from the 24-slot stator winding of Figs. 1 and 4.

The same coil grouping technique is applied to the 36-slot stator of Fig. 2. The conductor-current direction diagram is shown in Fig. 7, the coil groups are shown in Fig. 8, and their interconnection at the different pole numbers is shown in Fig. 9. Note that a coil group need not contain coils which have the same + or − designation at each pole number, so long as the designation changes in the same manner for all the coils between the different pole numbers. Thus, for example, the conductors of slots 7, 8 and 9 can be grouped with the conductor of slot 13. In the 4 pole arrangement, instead of a simple series connection of all the coil groups, they have been arranged as two sets, each of two pairs of groups in parallel. Connection in parallel can only be done if the groups in parallel have conductors located in relatively similar positions with regard to the poles. For example, in the 4 pole configuration, each of EF and XY represents the first three conductors of one pole and the second and third conductors of an opposite pole in a different part of the stator. Connection in parallel instead of in series is sometimes advantageous, since the total current is shared between the parallel branches. It can be shown that the flux density is inversely proportional to the number of turns in series, so that parallel interconnection can sometimes be used to get a ratio of flux densities between two pole numbers nearer to unity than might otherwise be obtained.

The switching requirement for the double layer winding can be explained briefly with reference to a specific example of a 36 slot motor with $p_1 = 2$, $p_2 = 3$, and $p_3 = 4$, in which p_1 is the unmodulated pole number.

The conductor distribution for the top layer of the double layer winding is shown in Fig. 10, and the corresponding direction of current flow at various pole numbers for phases A and B are given in Fig. 11. A careful inspection of the direction of current flow shows that it is possible for the coils to be grouped into 8 different entities as shown in Fig. 12.

Fig. 13 shows coil connections for a 36 slot motor with double layer windings to give (a) 4 poles, (b) 6 poles, (c) 8 poles, with two parallel circuits per phase at all three pole numbers, the switching requirement being shown at (d). It is shown in Fig. 13 that if there are 2 parallel paths for each of phases A and B, then 12 leads would be required to be brought out of the motor, and the leads should be connected to a 3-way 8-pole rotary switch as shown in Fig. 13(d). Note that in Fig. 13(d) the switch has been turned into position 2, and thus A/C is in contact with X via a centrifugal switch which is normally open, S to H, F to Q, X to L, C and J to Neutral.

Note, however, that the motor could only start (as a 2-phase motor) when the switch has been turned into position 1, since the motor becomes a pure single phase motor without any auxiliary winding when the switch is in position 2 or 3. In addition, if the motor is initially stationary, no current could flow in the coils when the switch is in position 2 or 3 since the centrifugal switch (c/s) is normally open if the motor is at standstill. The centrifugal switch would, however, be closed when the motor runs as a two-phase motor to a speed slightly below the minimum single-phase speed for which it is designed. In other words, it is if and only if the motor is running at a reasonably high speed that one could switch the motor from 2-phase to single phase operation. Furthermore, by means of this simple circuit, it is impossible to apply the mains voltage to the pure single phase motor while it is at standstill, thus avoiding the situation of the motor drawing excessive current while it is not trying to rotate at all.

Suitable switching requirements can be easily devised for motors which are required to operate in

either the capacitor start/induction run or capacitor start/capacitor run regimes at the unmodulated pole number.

In a similar manner, it is possible to have one series path for each of phases A and B, but 14 leads are required. Fig. 14 shows circuit connections and the corresponding switch requirements for a series-series-series connection in a 3 speed change-pole motor with starting torque at p_1 pole pairs. Note that 14 terminals from the motor and 19 independent circuits in the rotary switch are required. A 3-way 8-pole rotary switch in required. In Fig. 14(a) the motor is run as a permanent capacitor motor at this pole number.

If the e.m.f.'s of phases A and B are in time phase after modulation, then it is possible to arrange parallel operation between phases A and B, resulting in a simplified switching circuit. This is generally the case where the unmodulated phases are exactly symmetrical. (The case where $s = 36$, $p_1 = 2$, $p_2 = 3$, $p_3 = 4$ and p_1 is the unmodulated pole number is not symmetrical between phases A and B at the unmodulated pole number since the coil distribution for phases A and B are 4-5-4-5 and 5-4-5-4 respectively). Examples of such symmetrical cases are shown in Fig. 15 for $s = 48$, $p_1 = 2$, $p_2 = 3$, $p_3 = 4$ with p_1 as the unmodulated pole number. Here 10 terminals are required and the leads should be connected to a 3-way 7-pole rotary switch as shown in Fig. 15(d).

Note however that in general a 2-way 4-pole rotary switch is required for a 2-speed motor with series-series operation. The number of terminals required for such cases is 6. Fig. 21 shows circuit connections and switch requirements for series-series connections in a change-pole motor with starting torque at one pole number. Note that 6 terminals from the motor and 7 independent circuits in the rotary switch are required.

Note also that the number of terminals required for series (unmodulated)-parallel (modulated) operation is 5 only. An example of such a case is given in Fig. 16 for the case where $s = 36$, $p_1 = 3$, $p_2 = 2$ with p_1 as the unmodulated pole number. Fig. 16 shows circuit connections and switch requirements for series-parallel connections in a change-pole motor with starting torque at one pole number. Note that 5 terminals from the motor and 6 independent circuits in the rotary switch are required. A 2-way 3-pole rotary switch is all that is required (Fig. 16(f)). In Fig. 16(c) the motor is run as a permanent capacitor motor at this pole number.

It is of course possible to accomplish all the switching requirements by electronic means rather than using mechanical switches as described here.

The present invention therefore further provides a pole changing induction motor having an armature wound to provide polyphase operation on starting the motor at a first pole number and switching means operable for reconnecting coils or groups of coils of the winding to produce single-phase operation at one or more alternative pole numbers, the switching means incorporating a switch which connects the single-phase winding or windings with the current supply, the switch being responsive to the speed of the motor so that it closes only when the motor speed reaches a predetermined level, whereby operation of the switching means to select a said alternative pole number will not result in the supply of current to the single-phase winding if the motor speed is below said level.

In conventional P.A.M. motors, it is customary to represent the m.m.f. of a 2-phase machine by two sinusoidal waves mutually displaced by 90 electrical degrees. For a machine of p pole-pairs, the m.m.f. of the two phases are:

$$A_\theta = \text{m.m.f. of phase A} = K_1 \sin p\theta \quad (1)$$

$$B_\theta = \text{m.m.f. of phase B} = K_2 \sin(p\theta + \frac{\pi}{2}) = K_2 \cos p\theta \quad (2)$$

If the amplitudes K_1 and K_2 are space modulated by two sinusoidal waves, the resultant m.m.f. for each phase would be:

$$A_\theta = 2\,C_1 \sin p\theta \sin(k\theta + a)$$
$$= C_1[\cos((p-k)\theta - a) - \cos((p+k)\theta + a] \quad (3)$$

$$B_\theta = 2\,C_2 \sin(p\theta + \frac{\pi}{2})\sin(k\theta + b)$$

$$= C_2[\cos((p-k)\theta + \frac{\pi}{2} - b) - \cos((p+k)\theta + \frac{\pi}{2} + b] \quad (4)$$

where $K_1 = 2\,C_1 \sin(k\theta + a)$
$K_2 = 2\,C_2 \sin(k\theta + b)$
k = number of modulating cycles
a and b are constants taken to be 0 and $\frac{\pi}{2}$,

respectively, by Krishnamurthy and Rajaraman; and C_1 and C_2 are both equal to C in Krishnamurthy and Rajaraman's machines.

Adding equations (3) and (4) gives

$$A\theta + B\theta = +2\,C\cos(p-k)\theta \qquad (5)$$

Subtracting equation (4) from (3) gives

$$A\theta - B\theta = -2\,C\cos(p+k)\theta \qquad (6)$$

The above logic was used by Krishnamurthy and Rajaraman to produce a 3-speed motor. They have pointed out, however, that it is not possible to apply the above logic to the case where p = 2 and k = 1 since the two modulating waves cannot be displaced from each other by 90 degrees on the scale of $k\theta$. Referring to the top layer of a 24 slot, unmodulated 4-pole, double layer stator, as shown in Fig. 17, should make the points clear.

It is obvious from Figs. 17(a) and 17(b) that the modulating wave for phase A is a square wave as shown in Fig. 17(c). The modulating wave for phase B could, however, be either the square wave in Fig. 17(d) or 17(e). Consequently, the modulating waves are rather ill-defined when the original number of pole pairs per modulating pole pair is even, and the simple theory first proposed by Krishnamurthy and Rajaraman is not applicable. To overcome the difficulties of such pole combinations, Krishnamurthy has proposed using assymmetrical modulation, but this requires the omission of coils and the harmonic content is high.

A more detailed analysis indicates that the above restriction does not apply, and in particular, a and b are not necessarily 90 degrees (on the scale of $k\theta$) apart. In fact, for $p_1 = 2$, $p_2 = 3$ where p_1 and p_2 are the unmodulated and modulated pole-pair number respectively, a and b should not be 90 degrees apart. The following analysis, with reference to Fig. 18, should make the points clear.

Fig. 18(a) shows a 4 pole m.m.f. which is to be modulated by a single square wave (k = 1) as shown in Fig. 18(b). If the original of the modulating square wave and that of the 4 pole m.m.f. are displaced by *a* radians, half of the original m.m.f. will be reversed as shown in Fig. 18(c). Since there cannot be an abrupt change in m.m.f., the actual m.m.f. will be as shown in Fig. 18(d).

In general, the Fourier coefficient for a 2-pole m.m.f. which is modulated by one complete cycle (k = 1) of modulation can be found as follows:

In phase component

$$= a_{An} = \frac{1}{\pi}\Big[\int_0^{\pi-a} \sin p\theta \cos n\theta d\theta + \int_{\pi-a}^{2\pi-a} (2\sin p(\pi-a) - \sin p\theta)\cos n\theta d\theta + \int_{2\pi-a}^{2\pi} \sin p\theta \cos n\theta d\theta\Big]$$

$$= \frac{1}{\pi}\Big[\int_{2\pi-a}^{\pi-a} \sin p\theta \cos n\theta d\theta + \int_{\pi-a}^{2\pi-a} (2\sin p(\pi-a) - \sin p\theta)\cos n\theta d\theta\Big]$$

if n = odd p = odd $= \frac{-4}{n\pi}\sin p(\pi-a)\sin n a$

if n = even p = even = 0

if n = odd p = even $= \frac{2}{(p+n)\pi}\cos(p+n)a + \frac{2}{(p-n)\pi}\cos(p-n)a - \frac{4}{n\pi}\sin p(\pi-a)\sin n a$

if n = even p = odd $= \frac{2}{(p+n)\pi}\cos(p+n)a + \frac{2}{(p-n)\pi}\cos(p-n)a$

where n is the order of harmonic on the scale of mechanical degrees. The subscript A in a_{An} refers to phase A of a two-phase winding.

Similarly, the out of phase component for the m.m.f. shown in Fig. 18(d) can be found in a similar manner.

Out of phase component

$$= b_{An} = \frac{1}{\pi}\Big[\int_{2\pi-a}^{\pi-a} \sin p\theta \sin n\theta d\theta + \int_{\pi-a}^{2\pi-a} (2\sin p(\pi-a) - \sin p\theta)\sin n\theta d\theta\Big]$$

if n = odd p = odd $= -\frac{4}{n\pi}\sin p(\pi-a)\cos n a$

if n = even p = even = 0

if n = even p = odd $= -\frac{2}{(p+n)\pi}\sin(p+n)a + \frac{2}{(p-n)\pi}\sin(p-n)a$

if n = odd p = even $= -\frac{2}{(p+n)\pi}\sin(p+n)a + \frac{2}{(p-n)\pi}\sin(p-n)a - \frac{4}{n\pi}\sin p(\pi-a)\cos n a$

Likewise, the Fourier coefficient for phase B is found to be:

$$a_{Bn} = \text{In phase component} = \frac{4}{n\pi}\cos p(\pi - b)\sin n\, b$$

n = odd p = odd

$= 0$ n = even   p = even

$$= \frac{2}{(p+n)\pi}\sin(p+n)\,b + \frac{2}{(p-n)\pi}\sin(p-n)\,b - \frac{4}{n\pi}\cos p(\pi - b)\sin n\, b$$

n = odd   p = even

$$= \frac{2}{(p+n)\pi}\sin(p+n)\,b + \frac{2}{(p-n)\pi}\sin(p-n)\,b$$

n = even   p = odd

$$b_{Bn} = \text{Out of phase component} = \frac{4}{n\pi}\cos p(\pi - b)\cos n\, b$$

n = odd   p = odd

$= 0$ n = even   p = even

$$= +\frac{2}{(p+n)\pi}\cos(p+n)\,b - \frac{2}{(p-n)\pi}\cos(p-n)\,b$$

n = even   p = odd

$$= +\frac{2}{(p+n)\pi}\cos(p+n)\,b - \frac{2}{(p-n)\pi}\cos(p-n)\,b - \frac{4}{n\pi}\cos p(\pi - b)\cos n\, b$$

n = odd   p = even

The resultant Fourier coefficient when phase B is subtracted from phase A is:

$$\text{In phase component} = R_{an} = a_{An} - K_{re}a_{Bn} \text{ ——— } (7)$$

$$\text{Out of phase component} = R_{bn} = b_{An} - K_{re}b_{Bn} \text{ ——— } (8)$$

where R_{an} and R_{bn} are the resultant Fourier coefficients for the nth harmonic, and

$$K_{rc} = \frac{\text{number of effective conductors in phase B}}{\text{number of effective conductors in phase A}} = K_r\frac{K_{wB}}{K_{wA}}$$

$$\text{where } K_r = \frac{\text{actual number of conductors in phase B}}{\text{actual number of conductors in phase A}}$$

K_{wA}, K_{wB} are winding factors for phases A and B respectively.

If one wants to modulate a 4-pole m.m.f. to give 6 poles, one should put $R_{a1} = R_{b1} = 0$ in equations (7) and (8) in order to eliminate the 2-pole subharmonic.

In general, it is impossible to solve equations (7) and (8) analytically, but it is possible to solve the above two equations numerically by computer.

The solution for p = 2, n = 1, $K_{re} = 1$ is a = 81.7° and b = 143.3°.

In the case of the 4-pole, 24-slot machine, the values chosen are a = 82.5° (Fig. 17(f)) and b = 142.5°, and it can be shown that the 2-pole component has been eliminated all together in the resultant m.m.f.

In the case of the 4-pole, 36-slot machine, as shown in Fig. 19, the values chosen are a = 75° and b = 135° (Fig. 19(b)).

Note that according to equations (7) and (8), it is not possible to eliminate the two pole subharmonic for p = 2 if a = 0 and b = 90°. This conclusion is of course more realistic than those deduced from the simple theory of Krishnamurthy and Rajaraman.

Note also that for p = 3, one can eliminate the unwanted 8-pole harmonic to give 4-poles by putting a = 150° and b = 60°. Similarly, one can eliminate the 4-pole component to give 8 poles if a = 60° and b = 150°. This explains why the two modulating waves in Figs. 2(g) and 2(h) are not co-phasal in order to give the best m.m.f. for the two modulated pole numbers.

In the case of p = 2, n = 1, K_{re} = 1.2; the solution is a = 77.1°, b = 139.8°.

Likewise, it is possible to apply the more elaborate theory to any pole number combinations without any of the restrictions imposed by Krishnamurthy and Rajaraman.

Also, according to this new theory, it is possible for one to investigate the possibility of having modulating waves of different width. Such cases arise when one regards phases A and B as being a single phase winding after modulation. For example, in the case of s = 32, p_1 = 2, p_2 = 3 and p_3 = 4, with p_1 as the unmodulated pole number, it can be seen that for k = 1, it is better to have one side of the square wave to cover 15 slots, while the other side will cover the remaining 17 slots.

There are certain cases when one could not apply the modulating waves with the required length. For example, if the unmodulated pole pair number is 3, and k = 2, then it is clear that the modulating waves need to be unsymmetrical as shown in Fig. 20 since some half-cycles of the modulating wave would cover 2 pole lengths while the other half-cycles will cover 1 pole length only. In such cases, it is obvious that some subharmonics will be generated, but they are of course not detrimental to the performance of the motor.

In order to demonstrate the practicality of the proposed technique, this appendix gives the test results of the triple speed winding whose harmonic contents are listed in Table 3.

A conventional 36 slot, single-phase motor frame was used to accommodate the triple-speed winding. In its standard form, this stator is wound as a three-phase, 6-pole motor giving an output power of 250W. Each of the 48 bars in the rotor is skewed by 2 bars.

The rated performance figures for the triple-speed 4/6/8 pole motor with a 28μF capacitor in the 4-pole connection is as given in Table A1.

	4 pole	6 pole	8 pole
Output Power	450 W	150 W	75 W
Speed	1420 rev/min	950 rev/min	690 rev/min
Efficiency	69%	50.5%	31.5%
Power factor	0.950	0.693	0.510
Current	3.12 A	1.95	2.12 A
Starting Torque	39.8% of Full Load Torque	—	—

Table A1 Rated performance figures of the 4/6/8 pole motor at an operating phase voltage of 220 V.

Furthermore, the complete range of torque/speed characteristics of the motor is shown in Fig. 22. Note that the test was carried out at an operating voltage of 170 V in order to avoid overheating of the motor.

This motor is suitable for fan driving duties in which the torque increases approximately with the square of its operating speed.

CLAIMS

1. An induction electrical machine having a ferromagnetic core with a number of slots, a double layer winding occupying those slots, the winding comprising two phase-windings for two-phase operation at a first pole number, the top layer of the double layer winding having the conductors assigned to s/4p (or an integral number adjacent thereto if it is a non-integer) successive slots for each pole of each of the two phase-windings (wherein s is the number of stator slots and p is the number of pole pairs), the coil pitch being selected so as to produce acceptable harmonics for the two-phase operation, and switching means for reconnecting coils or groups of coils of the two phase-windings in two different ways according to the method of pole amplitude modulation to convert them into a single phase winding at each of respective second and third pole numbers, wherein the positions of both modulating waves producing the second pole number are different from those producing the third pole number.

2. An induction electrical machine having a ferromagnetic core with a number of slots, a double layer winding occupying those slots, the winding comprising two phase-windings for two-phase operation at a first pole number, the top layer of the double layer winding having the conductors assigned to s/4p (or an integral number adjacent thereto if it is a non-integer) successive slots for each pole of each of the two phase-windings (wherein s is the number of stator slots and p is the number of pole pairs), the coil pitch being selected so as to produce acceptable harmonics for the two-phase operation, and switching means for reconnecting coils or groups of coils of the two phase-windings according to the method of pole amplitude modulation to convert them into a single phase winding at a second pole number, the modulating waves applied to the two phase-windings being mutually displaced around the machine axis by greater or less than 90° measured on the scale $k\theta$ wherein k is the number of modulating pairs in one revolution and θ is mechanical degrees around the machine axis.

3. An induction electrical machine having a ferromagnetic core with a number of slots, a double layer winding occupying those slots, the winding comprising two phase-windings for two-phase operation at a first pole number, the top layer of the double layer winding having the conductors assigned to s/4p (or an integral number adjacent thereto if it is a non-integer) successive slots for each pole of each of the two phase-windings (wherein s is the number of stator slots and p is the number of pole pairs), the coil pitch being selected so as to produce acceptable harmonics for the two-phase operation, and switching means for reconnecting coils or groups of coils of the two phase-windings to

convert them into a single phase winding at a second pole number, such that the top layer of the double layer winding has the conductors assigned to $s/2p_2$ (or an integral number adjacent thereto if it is a non-integer) successive slots for each pole of the second pole number (wherein s is the number of stator slots and p_2 is the number of pole pairs at the second pole number), except that one or more coils providing conductors in the top layer adjacent one end of each of alternate $s/2p_2$ groups of conductors are reversed.

4. An induction electrical machine having a ferromagnetic core with a number of slots, a double layer winding occupying those slots, the winding comprising two phase-windings for two-phase operation at a first pole number, the top layer of the double layer winding having the conductors assigned to s/4p (or an integral number adjacent thereto if it is a non-integer) successive slots for each pole of each of the two-phase windings (wherein s is the number of stator slots and p is the number of pole pairs), the coil pitch being selected so as to produce acceptable harmonics for the two-phase operation, and switching means for reconnecting coils or groups of coils of the two-phase windings, according to a method of pole amplitude modulation in which separate pole amplitude modulating waves are applied to the phase-windings, the two modulating waves being displaced from each other around the machine axis by less than 180°, to convert the two phase-windings into a single phase-winding at a second pole number.

5. An induction electrical machine according to claim 4 wherein the switching means provides two alternative reconnections giving single phase-windings at respectively second and third pole numbers of which one is above and one is below the first pole number.

6. An induction electrical machine according to claim 2 or claim 3 wherein the switching means provides two alternative reconnections giving single phase windings at respectively second and third pole numbers.

7. An induction electrical machine according to claim 1 or claim 6 wherein the two phase operation is at the lowest or highest of the three alternative pole numbers.

8. A pole changing induction motor having an armature wound to provide polyphase operation on starting the motor at a first pole number and switching means operable for reconnecting coils or groups of coils of the winding to produce single-phase operation at one or more alternative pole numbers, the switching means incorporating a switch which connects the single-phase winding or windings with the current supply, the switch being responsive to the speed of the motor so that it closes only when the motor speed reaches a predetermined level, whereby operation of the switching means to select a said alternative pole number will not result in the supply of current to the single-phase winding if the motor speed is below said level.

9. An induction electrical machine having a ferromagnetic core wound with concentric coils substantially as described herein with reference to the accompanying drawings.

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FIG.1(a)

SLOT NO. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

TOP LAYER A A A B B B -A -A -A -B -B -B A A A B B B -A -A -A -B -B -B

BOTTOM LAYER A B B B -A -A -A -B -B -B A A A B B B -A -A -A -B -B -B A A

FIG.1(b)

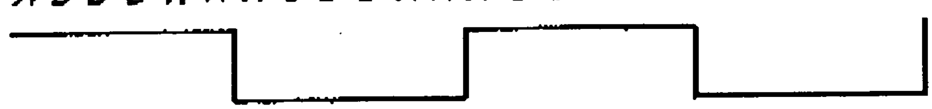

FIG.1(c)

A A A B -B -B -A -A A B B B -A -A -A -B B B A A -A -B -B -B

A B B B -A -A -A -B B B A A -A -B -B -B A A A B -B -B -A -A

FIG.1(d)

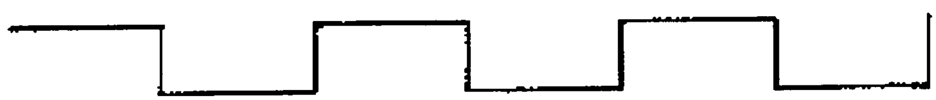

FIG.1(e)

A A A -B -B -B A A A -B -B -B A A A -B -B -B A A A -B -B -B

-A B B B -A -A -A B B B -A -A -A B B B -A -A -A B B B -A -A

FIG.1(f)

FIG.1(g)

-A A A B -B -B -A -A -A B B B -A -A -A -B B B A A -A -B -B -B

A B B B A -A -A -B B B A A A -B -B -B A A A B B -B -A -A

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36

FIG. 2(a)

A A A B B B -A -A -A -B -B -B A A A B B B -A -A -A -B -B -B A A A B B B -A -A -A -B -B -B
A A A B B B -A -A -A -B -B -B A A A B B B -A -A -A -B -B -B A A A B B B -A -A -A -B -B -B

FIG. 2(b)

A A A B B B A A A -B -B -B -A -A -A -B -B -B A A A B B B A A A -B -B -B -A -A -A -B -B -B
A A A B B B -A -A -A -B -B -B -A -A -A B B B A A A B B B -A -A -A -B -B -B -A -A -A B B B

FIG. 2(c)

A A A B -B -B -A -A -A B B B A -A -A -B -B -B A A A B -B -B -A -A -A B B B A -A -A -B -B -B
-A A A B B B -A -A -A -B B B A A A -B -B -B -A A A B B B -A -A -A -B B B A A A -B -B -B

FIG. 2(d)

FIG. 2(e)

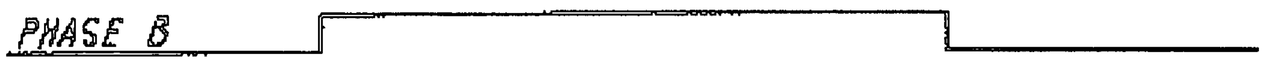

FIG. 2(f)

FIG. 2(g)

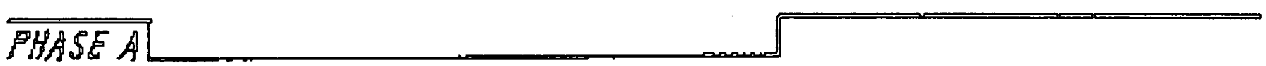

FIG. 2(h)

FIG. 2(i)

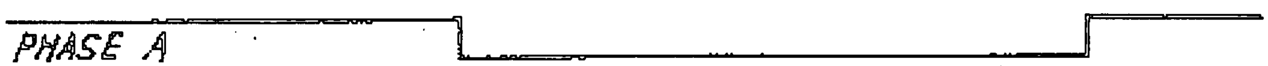

FIG. 2(j)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
A A A A B B B B-A-A-A-A-B-B-B-B A A A A B B B B-A-A-A-A-B-B-B-B
A B B B B-A-A-A-A-B-B-B-B A A A A B B B B-A-A-A-A-B-B-B-B A A A

FIG. 3(a) CONDUCTOR DISTRIBUTION FOR 4 POLES, UNMODULATED

A A A A B-B-B-B-A-A A A B B B B-A-A-A-A-B-B B B A A A-A-B-B-B-B
A B B B B-A-A-A-A-B B B B A A-A-A-B-B-B-B A A A A B B-B-B-A-A-A

FIG. 3(b) CONDUCTOR DISTRIBUTION FOR 6 POLES, MODULATED

FIG. 3(c) MODULATING WAVE FOR PHASE A

FIG. 3(d) MODULATING WAVE FOR PHASE B

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FIG. 4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
4 POLES	+	+	+				−	−	−				+	+	+				−	−	−				PHASE A
6 POLES	−	+	+				−	−	−				−	−	−				+	+	−				
8 POLES	+	+	+				+	+	+				+	+	+				+	+	+				
4 POLES				+	+	+				−	−	−				+	+	+				−	−	−	PHASE B
6 POLES				+	−	−				+	+	+				−	−	+				−	−	−	
8 POLES				−	−	−				−	−	−				−	−	−				−	−	−	

FIG. 5

E [1 13 14 15] F   X [2 3] Y   G [7 8 9 21] H   C [19 20] D

L [4 18] M   P [5 6 16 17] Q   R [10 11 12] S   T [22 23 24] K

FIG. 6

4 POLES
PHASE A   XY—CD—EF—GH——TO R
PHASE B   RS—LM—JK—PQ——TO X

6 POLES   PQ—XY—FE—DC—GH—RS—KJ—ML

8 POLES   PQ—XY—DC—EF—SR—HG—KJ—LM

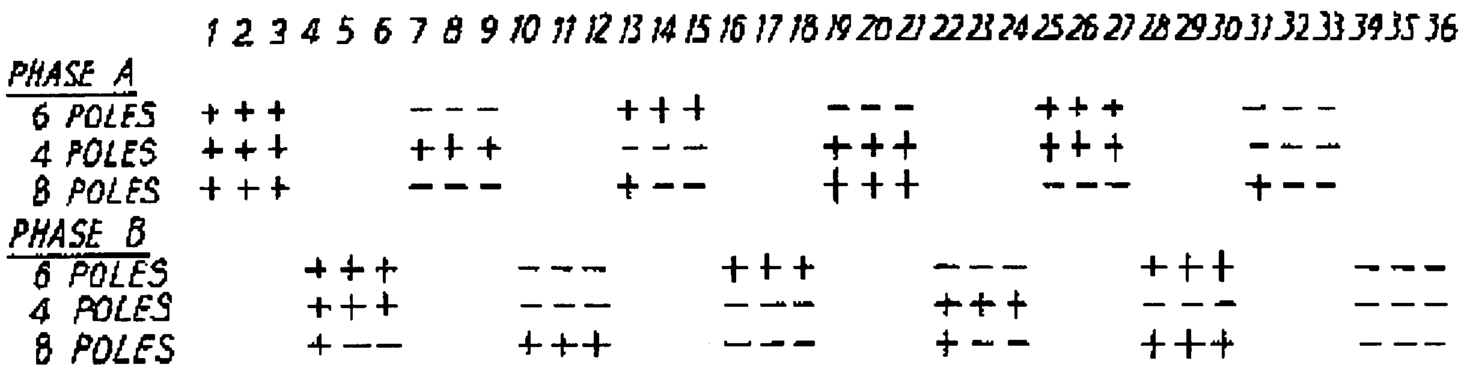

FIG.7

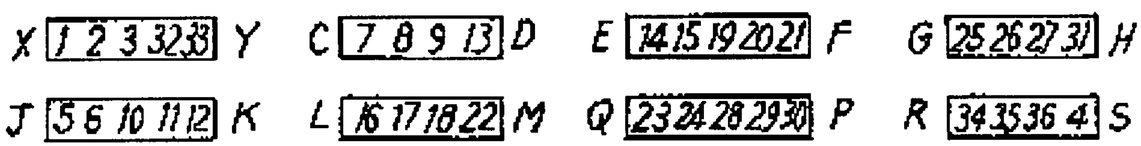

FIG.8

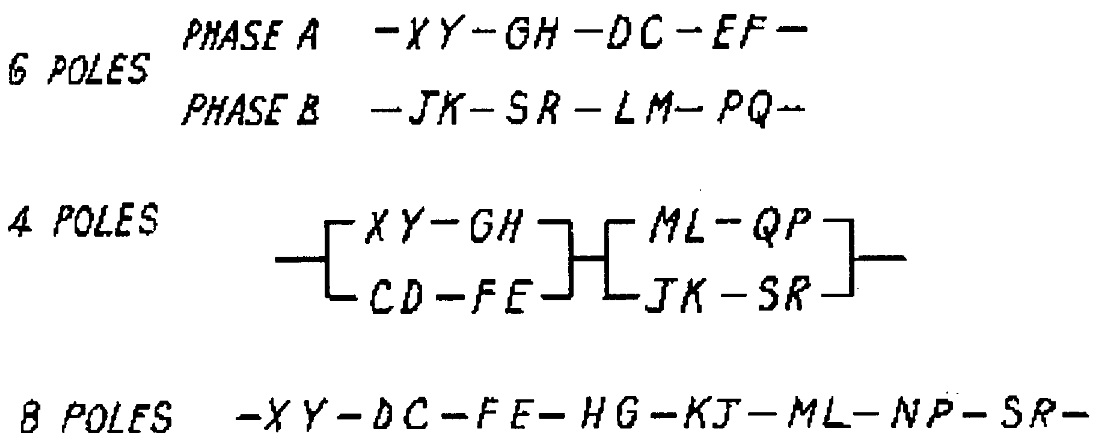

FIG.9

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
4 POLES	A	A	A	A	B	B	B	B	B	-A	-A	-A	-A	-A	-B	-B	-B	-B	A	A	A	A	B	B	B	B	B	-A	-A	-A	-A	-A	-B	-B	-B	-B
6 POLES	A	A	A	A	B	B	-B	-B	-B	-A	-A	-A	A	A	B	B	B	B	-A	-A	-A	-A	-B	-B	B	B	B	A	A	A	-A	-A	-B	-B	-B	-B
8 POLES	A	A	A	A	B	-B	-B	-B	-B	A	A	A	A	A	-B	-B	-B	-B	A	A	A	A	B	-B	-B	-B	-B	A	A	A	A	A	-B	-B	-B	-B

FIG.10 CONDUCTOR DISTRIBUTION OF THE TOP LAYER AT 4, 6 AND 8 POLES

PHASE A	4 POLES	++++	-----	++++	-----
	6 POLES	++++	---++	----	+++--
	8 POLES	++++	+++++	++++	+++++
PHASE B	4 POLES	+++++	----	+++++	----
	6 POLES	++---	++++	--+++	----
	8 POLES	+----	----	+----	----

FIG.11 DIRECTION OF CURRENT FLOW FOR PHASES A AND B AT 4, 6 AND 8 POLES

X—[1 2 3 4]—Y G—[10 11 12 31 32]—H C—[13 14 28 29 30]—D E—[19 20 21 22]—F

J—[33 34 35 36 5]—K L—[6 25 26 27]—M P—[7 8 9 24]—Q R—[15 16 17 18 23]—S

FIG.12 GROUPING OF COILS ACCORDING TO DIRECTION OF CURRENT FLOW

PARALLEL CIRCUIT

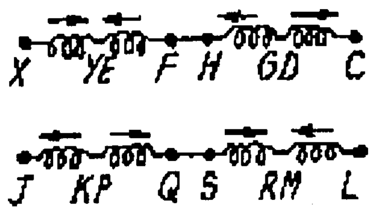

FIG.13(a)

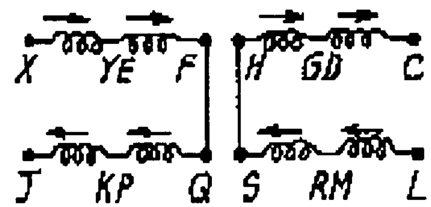

FIG.13(b)

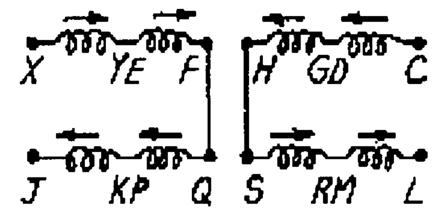

FIG.13(c)

POSITION 1

POSITION 2

POSITION 3

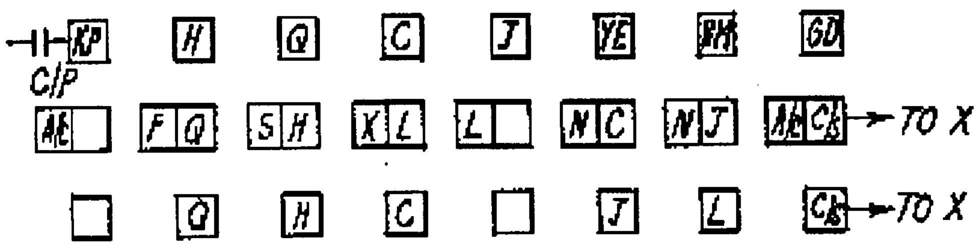

FIG.13(d)

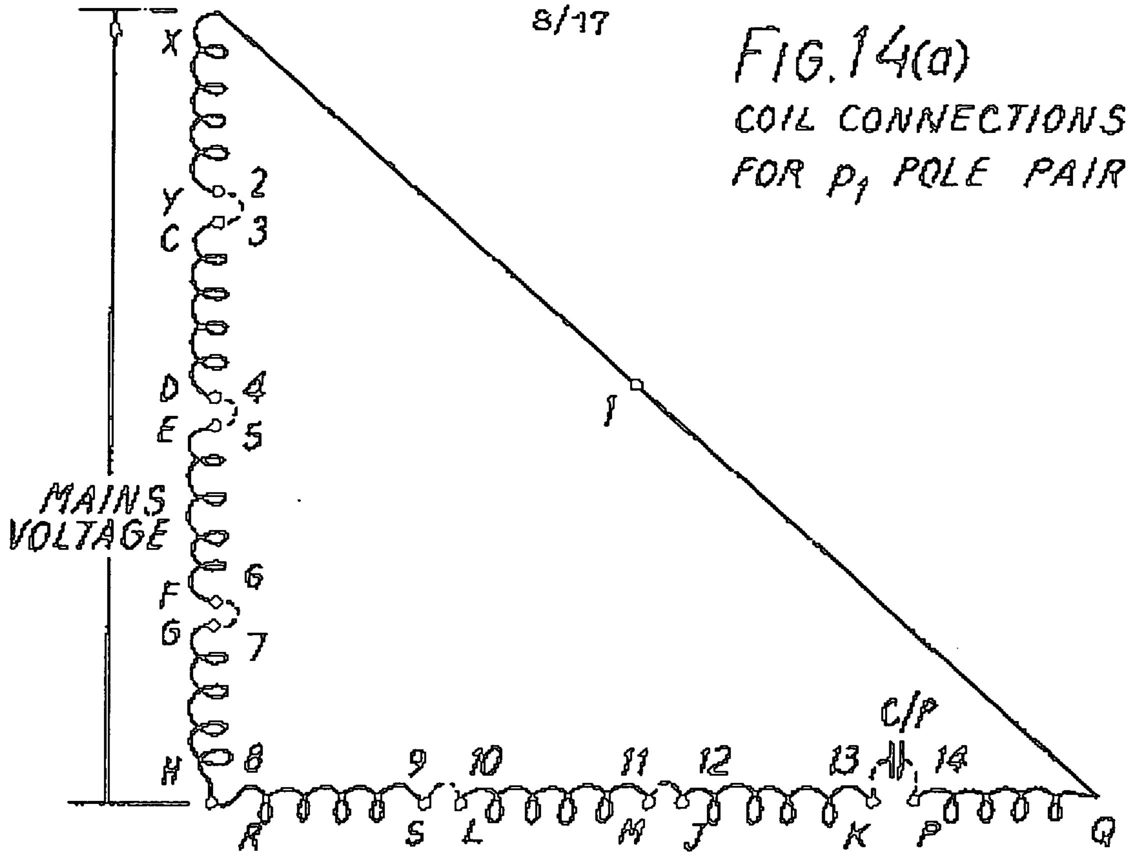

FIG. 14(a)
COIL CONNECTIONS
FOR p_1 POLE PAIRS

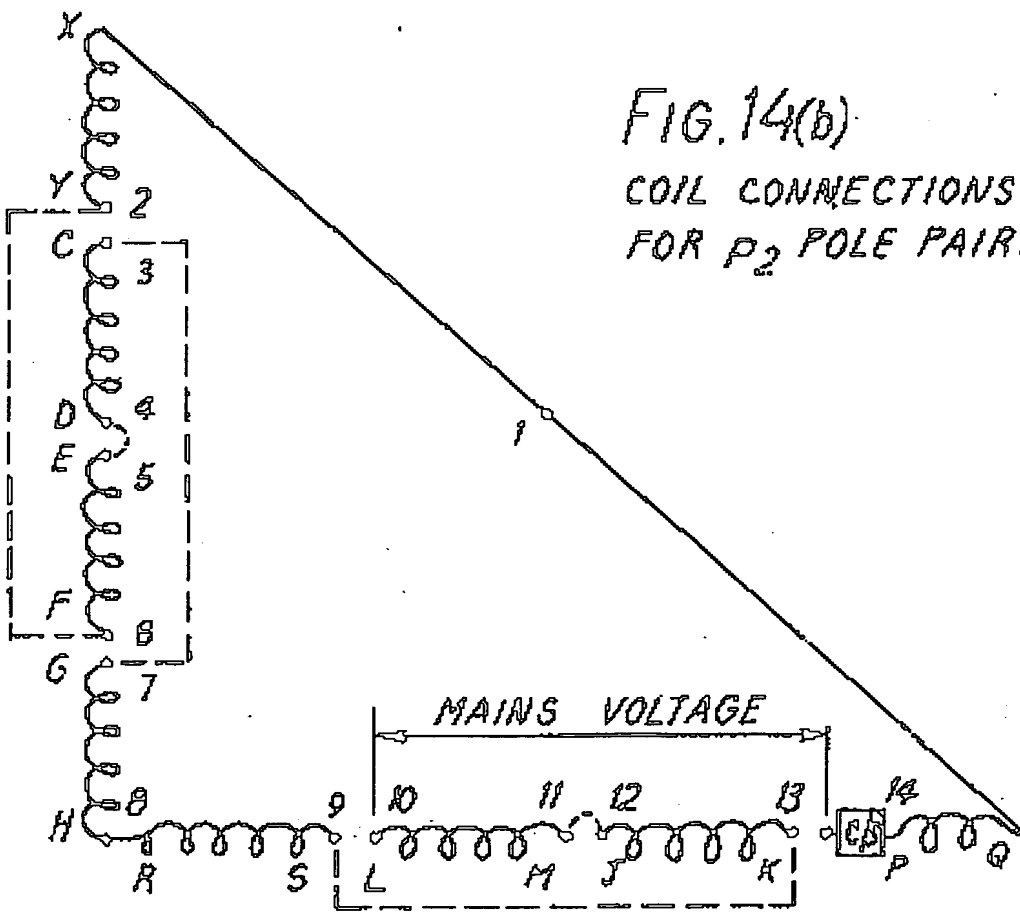

FIG. 14(b)
COIL CONNECTIONS
FOR p_2 POLE PAIRS

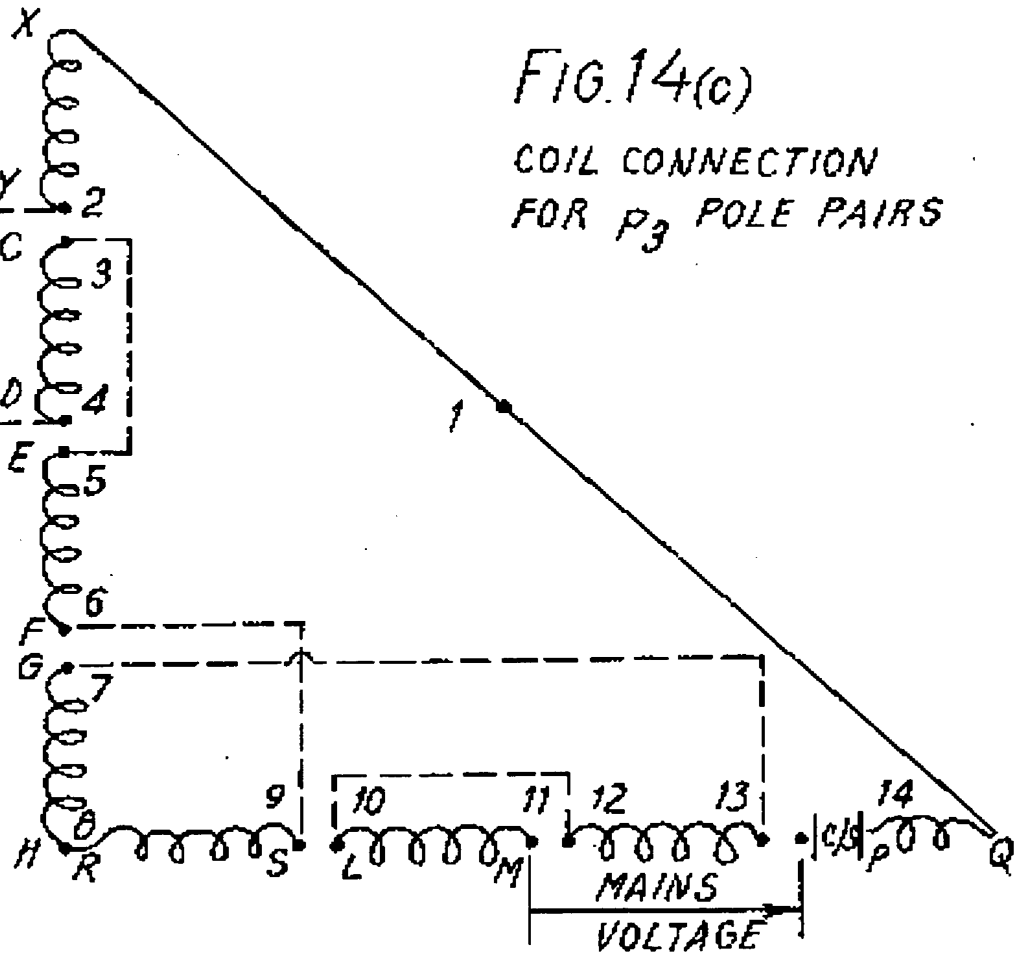

FIG. 14(c)

COIL CONNECTION FOR P_3 POLE PAIRS

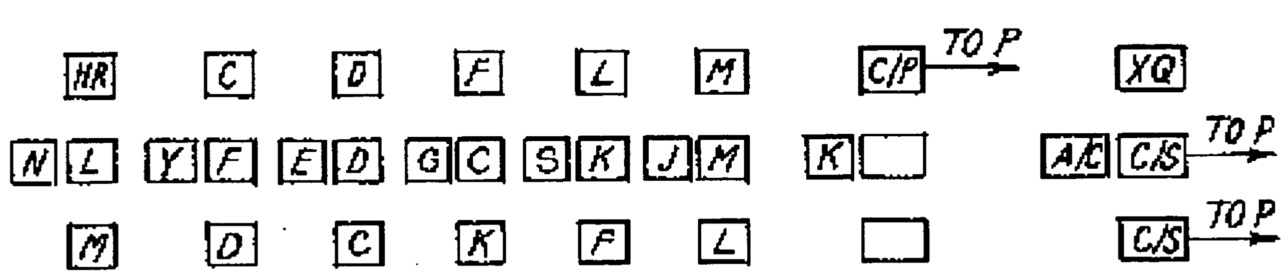

FIG. 14(d) SWITCH CIRCUIT FOR THE 3 SPEED MOTOR

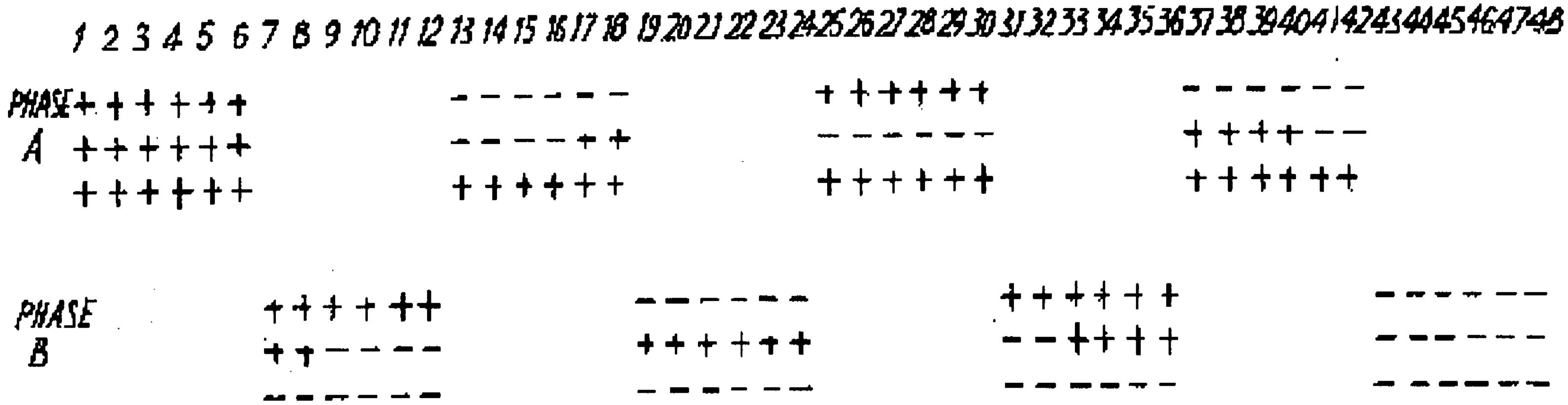

FIG 15(a)

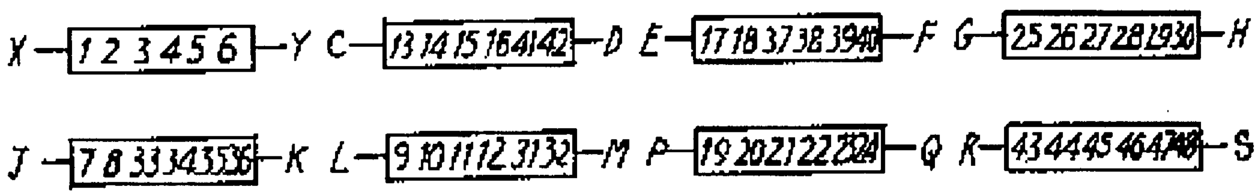

FIG. 15(b)

GROUPING OF COILS

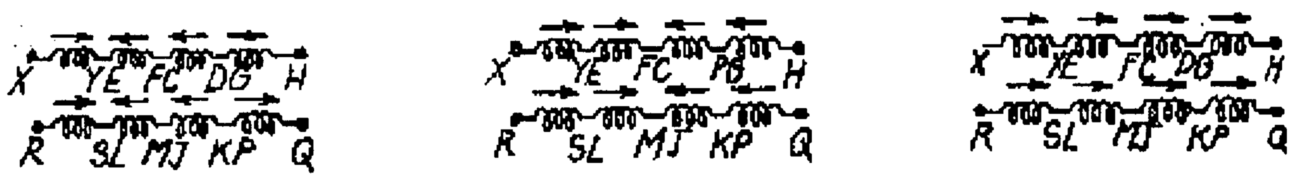

FIG. 15 (c)

COIL SEQUENCE

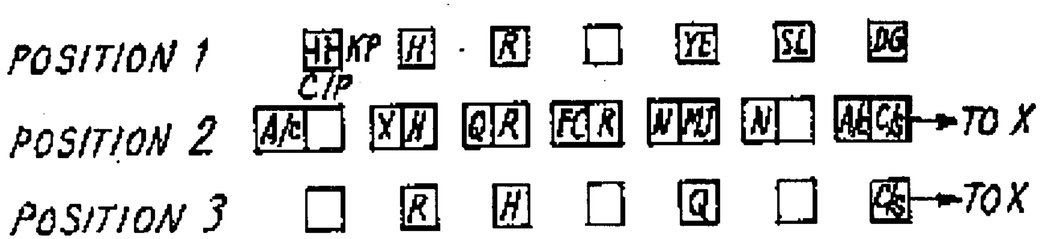

FIG. 15(d)

SWITCHING CONNECTIONS

		1 2 3	4 5 6	7 8 9	10 11 12	13 14 15	16 17 18	19 20 21	22 23 24	25 26 27	28 29 30	31 32 33	34 35 36
PHASE A	6 POLE	+ + +		− − −		+ + +		− − −		+ + +		− − −	
	4 POLE	+ + +		+ + +		− − −		+ + +		+ + +		− − −	
PHASE B	6 POLE		+ + +		− − −		+ + +		− − −		+ + +		− − −
	4 POLE		+ + +		− − −		− − −		+ + +		− − −		− − −

FIG.16(a) CONDUCTOR DISTRIBUTION

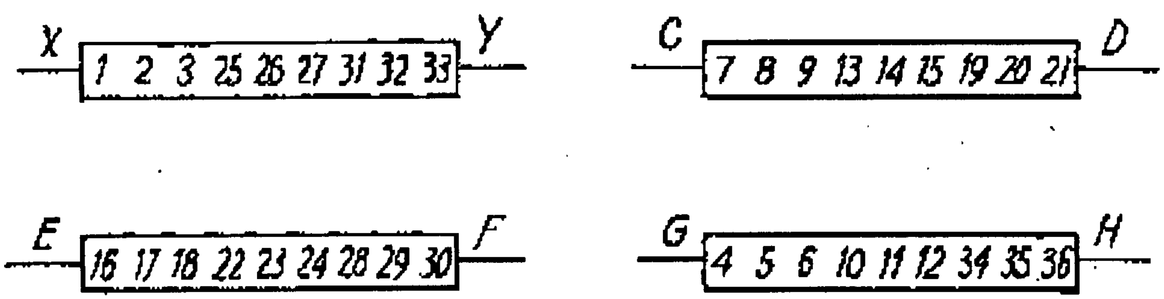

FIG.16(b) COIL GROUPINGS

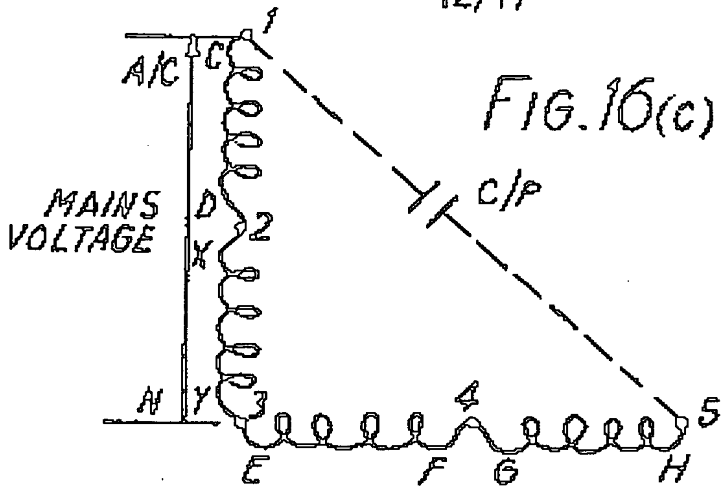

FIG. 16(c) COIL CONNECTIONS FOR P_1 POLE PAIRS

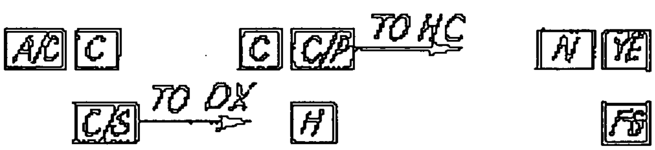

FIG. 16(d) SWITCH CIRCUIT CORRESPONDING TO FIG 16(c)

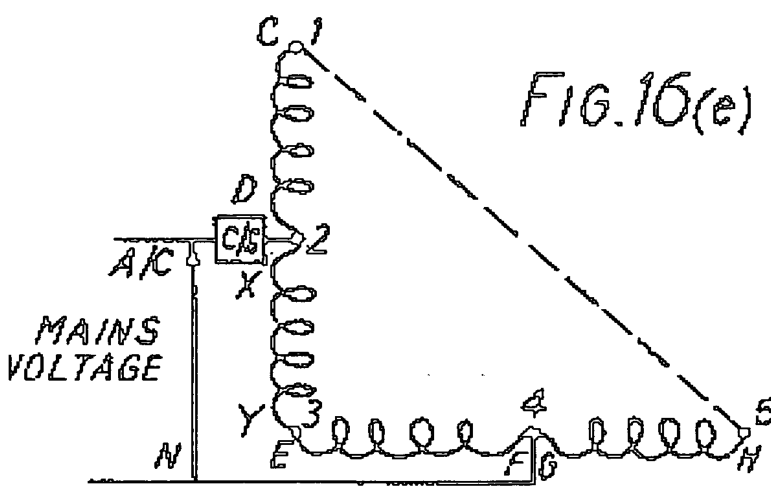

FIG. 16(e) COIL CONNECTIONS FOR P_2 POLE PAIRS

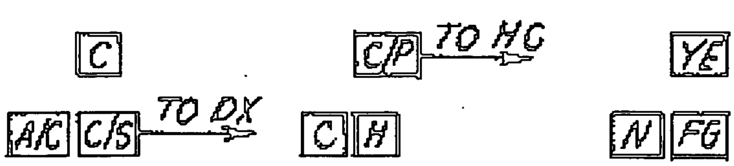

FIG. 16(f) SWITCH CIRCUIT CORRESPONDING TO FIG 16(e)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

A A A B B B -A -A -A -B -B -B A A A B B B -A -A -A -B -B -B

FIG.17(a) TOP LAYER COIL DISTRIBUTION
UNMODULATED 4-POLE STATOR

A A A B B B -A -A -A B B B -A -A -A -B B B A A A -B -B -B

FIG.17(b) MODULATED COIL DISTRIBUTION

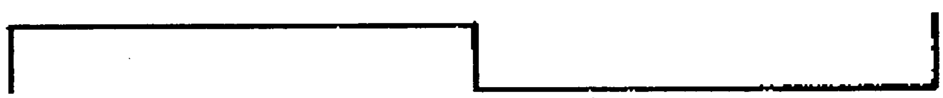

FIG.17(c) MODULATING WAVE FOR PHASE A

FIG.17(d) MODULATING WAVE FOR PHASE B

FIG.17(e) MODULATING WAVE FOR PHASE B

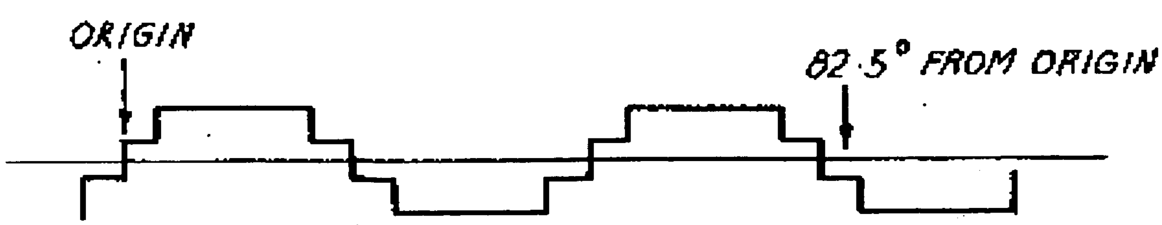

FIG.17(f) M.M.F. FOR THE TOP LAYER OF PHASE A

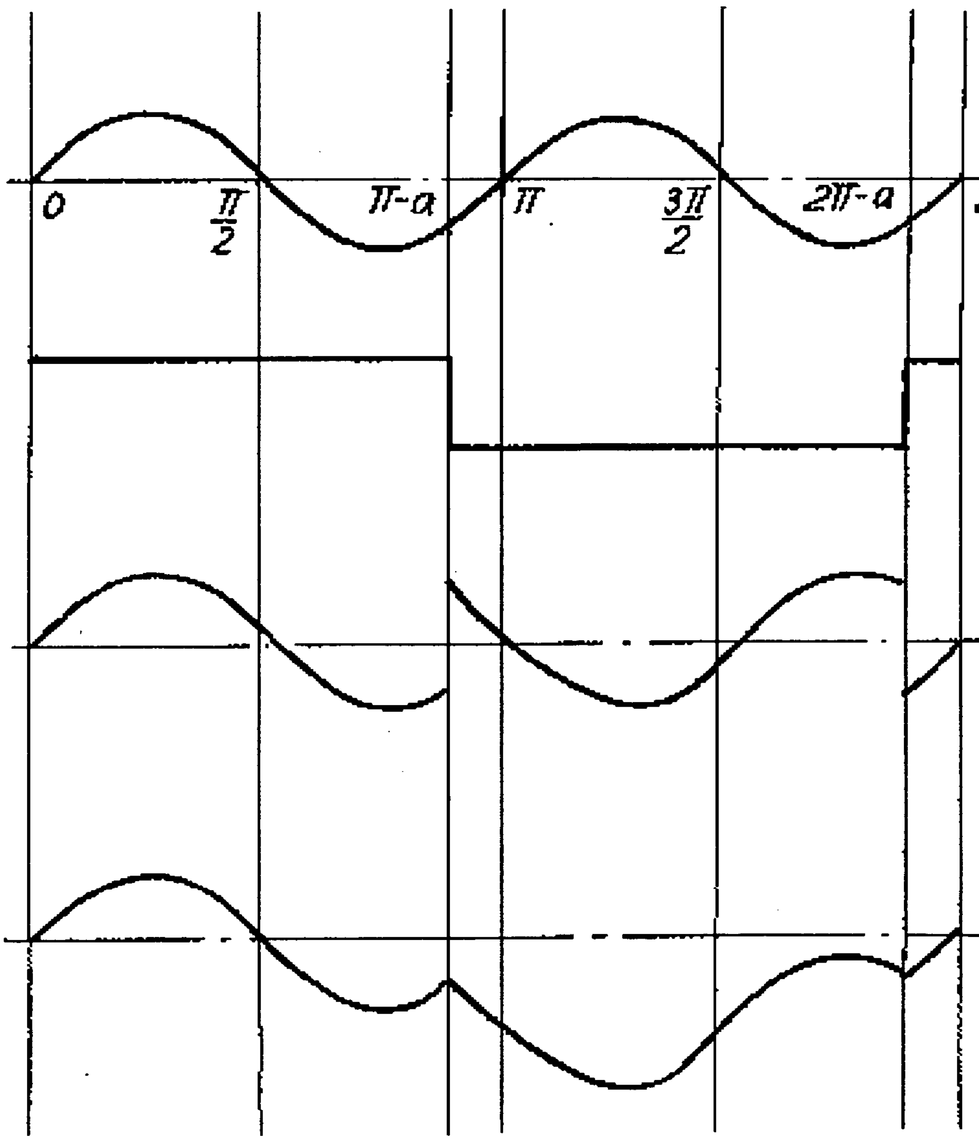

FIG.18(a) UNMODULATED 4 POLE M.M.F.

FIG.18(b) MODULATING WAVE DISPLACED FROM THE 4 POLE M.M.F.

FIG.18(c) RESULTANT M.M.F. AFTER MODULATION BY (b)

FIG.18(d) ACTUAL M.M.F.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
A	A	A	A	B	B	B	B	B	-A	-A	-A	-A	-A	-B	-B	-B	-B	A	A	A	A	B	B	B	B	B	-A	-A	-A	-A	-A	-B	-B	-B	-B

FIG. 19(a) TOP LAYER COIL DISTRIBUTION OF AN UNMODULATED 4 POLE STATOR WITH 36 SLOTS

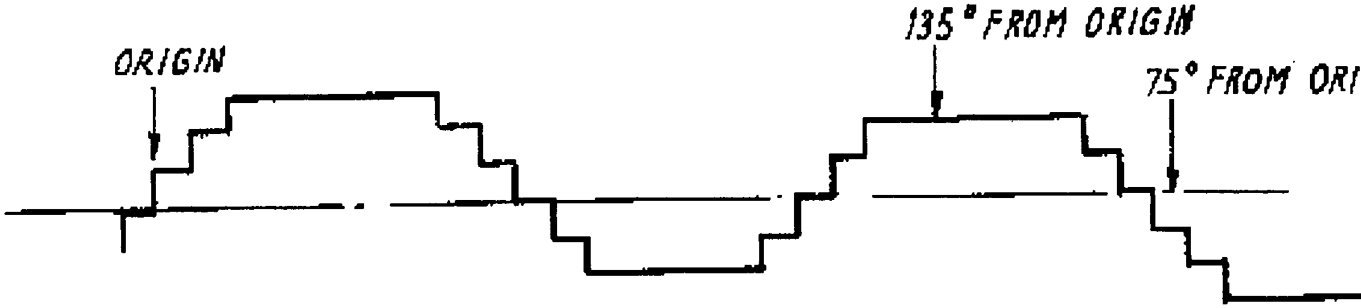

FIG. 19(b) M.M.F. FOR THE TOP LAYER OF PHASE A

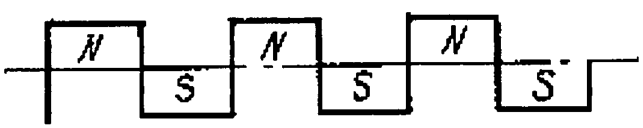

FIG. 20(a) UNMODULATED POLES

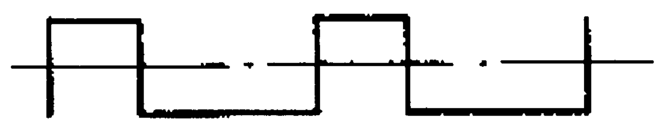

FIG. 20(b) MODULATING WAVES

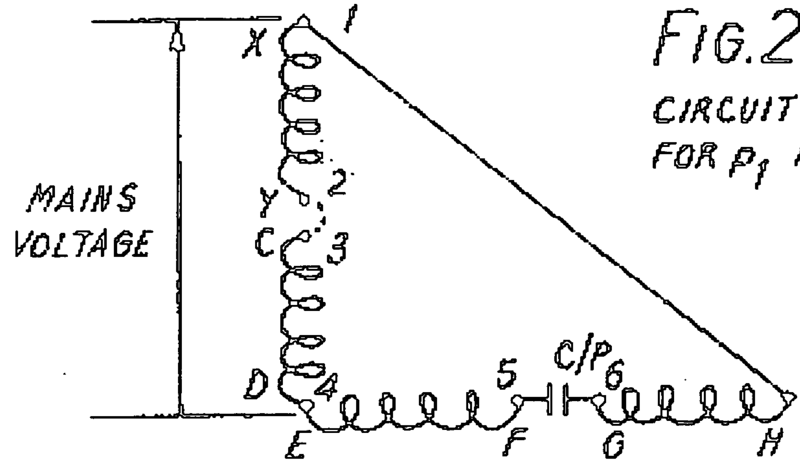

FIG. 21(a)
CIRCUIT CONNECTIONS
FOR p_1 POLE PAIRS

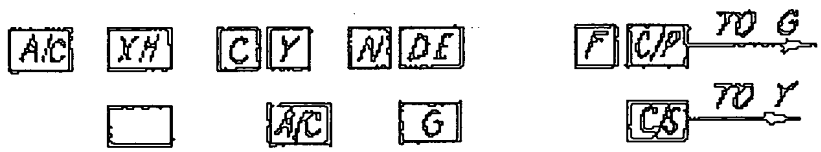

FIG. 21(b) SWITCH CIRCUIT CORRESPONDING TO FIG. 21(a)

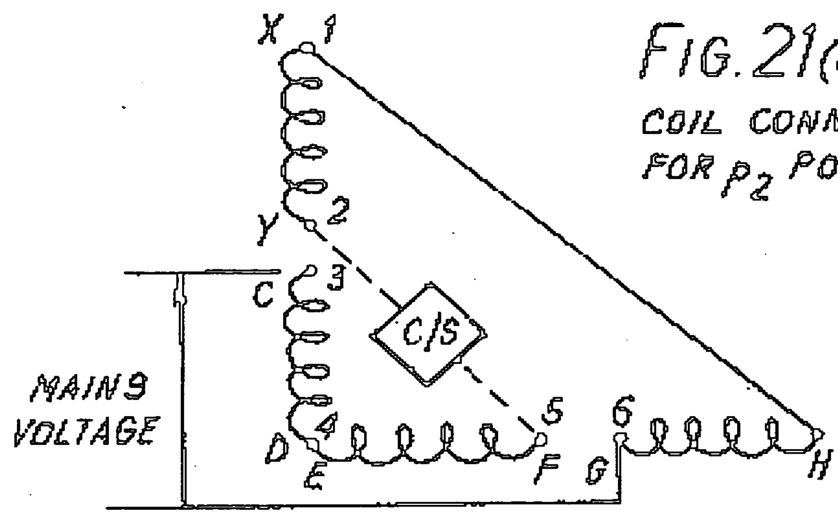

FIG. 21(c)
COIL CONNECTIONS
FOR p_2 POLE PAIRS

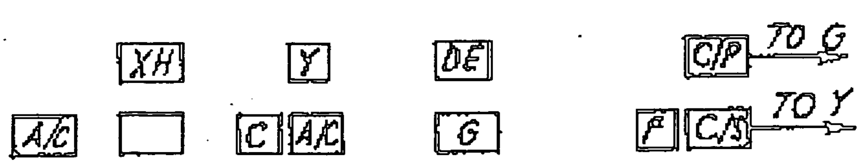

FIG. 21(d) SWITCH CIRCUIT CORRESPONDING TO FIG. 21 (c)

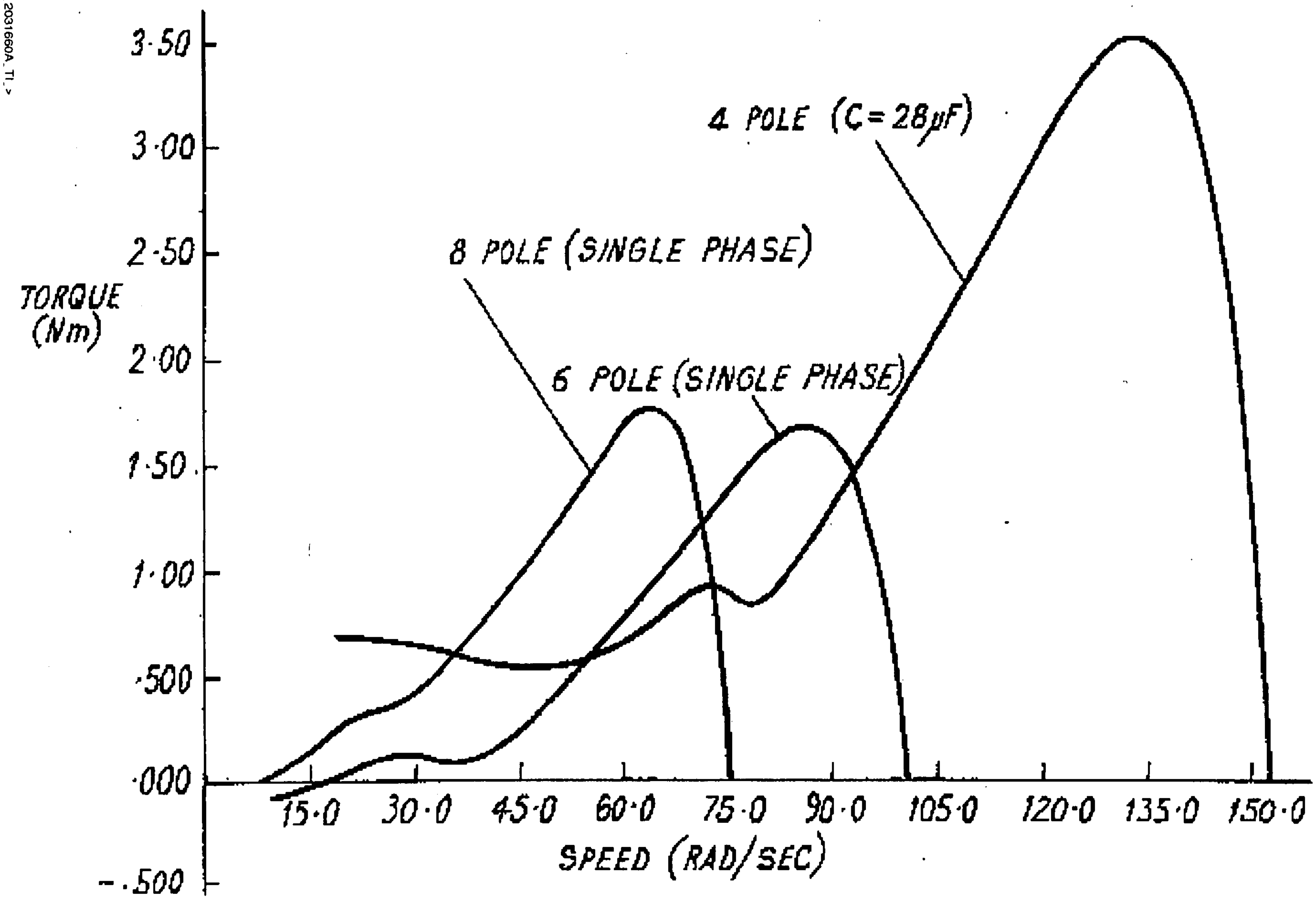

FIG. 22 TORQUE / SPEED CHARACTERISTIC OF THE 4/6/8 POLE MOTOR